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OPTIMIZING MULTI-SHIP, MULTI-MISSION OPERATIONAL PLANNING FOR THE JOINT FORCE MARITIME COMPONENT COMMANDER

by

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March 2009

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Operational-level planners in Maritime Operations Centers aim to assign naval forces in support of combatant commanders efficiently and effectively, but they lack a software-based planning tool to develop optimal ship employment schedules. They must assign ships to particular missions spread throughout numerous regions over a particular time horizon to meet the combatant commander's force requirements. Currently, this is a manual process. We present Navy Mission Planner (NMP), a decision aid based on an integer linear program that allows efficient generation of candidate employment schedules. NMP uses constrained, stack-based enumeration of candidate employment schedules over the feasible region. Total enumeration can produce an enormous number of schedules—easily reaching quadrillions of feasible solutions. By constraining the enumeration to eliminate impractical schedules, we can manage the computational burden and provide the naval planner useful solutions containing a near-optimal set of employment schedules for each assigned ship over the planning horizon. We submit a realistic scenario and provide a credible, face-valid solution to the multi-ship, multi-mission assignment problem, with sets of employment schedules that are as good as or better than sets produced manually.

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OPTIMIZING MULTI-SHIP, MULTI-MISSION OPERATIONAL PLANNING FOR THE JOINT FORCE MARITIME COMPONENT COMMANDER

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LIST OF ABBREVIATIONS AND ACRONYMS

AD	Air Defense
ASW	Antisubmarine Warfare
C3F	Commander, U.S. Third Fleet
CFMCC	Combined Forces Maritime Component Commander
CMC	Concurrent Mission Capable
COCOM	Combatant Command
CONOPS	Concept of Operations
FFC	Fleet Forces Command
GAMS	General Algebraic Modeling System
Intel	Intelligence
JFMCC	Joint Force Maritime Component Commander
JP	Joint Publication
MCM	Mine Countermeasures
MHQ	Maritime Headquarters
MIO	Maritime Interception Operations
MOC	Maritime Operations Center
NCC	Naval Component Commander
NMP	Navy Mission Planner
NSFS	Naval Surface Fire Support
NWDC	Navy Warfare Development Command
NWP	Navy Warfare Publication
OPCON	Operational Control
PACFLT	Commander, U.S. Pacific Fleet
SubIntel	Submarine Intelligence Collection
SUW	Surface Warfare
TACMEMO	Tactical Memorandum
TACON	Tactical Control
TBMD	Theater Ballistic Missile Defense
VBA	Visual Basic

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EXECUTIVE SUMMARY

Maritime component commanders employ naval forces in support of the combatant commander. To support the commander's goals, staff planners in Maritime Operations Centers assign particular ships to particular missions in particular regions at particular times. In this era of limited resources, requirements often exceed resources, and the challenge for planners is to assign available resources efficiently and effectively. They currently lack a software-based planning tool to develop optimal ship employment schedules.

There are many factors involved in building a fleet schedule. Ships flow in and out of theater. Areas of operations typically cover large geographic areas. Some areas require multiple missions to meet the combatant commander's force requirements, and some missions require support from multiple units.

Currently, fleet scheduling is a manual process. Schedulers must juggle numerous requirements, and they typically do so with the help of a whiteboard and marker pens.

Navy Mission Planner (NMP) seeks to remove some of the complexity and reduce the time involved in mission planning and course of action development. NMP is a decision aid based on an integer linear program that takes the planner's inputs and returns a set of optimized ship employment schedules. The user inputs regions, or operating areas, and defines adjacency arcs connecting the regions. The planner then defines which missions are required on which days in which regions and assigns the value of each mission, thus setting the priorities in case requirements exceed resources. The planner also defines any prerequisite missions to be fully accomplished prior to the commencement of the desired mission. The user then notes the available ships, the days these ships are in theater, each ship's entry point into the area of operations, and set of concurrent mission capabilities (CMCs) available to that ship. CMCs define the ship's ability to complete multiple missions concurrently.

The NMP user interface is a Microsoft Excel spreadsheet. Excel, through Visual Basic code, enumerates candidate schedules for each ship. Because total enumeration can produce an enormous number of schedules—easily reaching quadrillions of feasible solutions, we limit the enumeration by defining the maximum number of schedules as well as a subset, the maximum number of schedules per ship. By constraining the enumeration process, we can provide the naval planner useful solutions containing the optimal set of employment schedules for each assigned ship over the planning horizon.

Excel sends the set of inputs to the General Algebraic Modeling System (GAMS). GAMS uses the commercial solver CPLEX to find the optimal set of ship employment schedules that maximizes the aggregate value of all maritime missions accomplished over the planning horizon.

NMP supports ever-changing scenarios and provides credible, face-valid solutions to the multi-ship, multi-mission assignment problem. NMP shifts the computational burden away from the operational planner and onto the computer. The CPLEX solver ensures that the sets of employment schedules are as good as or better than any set produced manually.

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I dedicate this work to my beloved father. While he did not see the completion of this project, his memory remains to guide me through all that lies ahead.

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I. INTRODUCTION

A. PURPOSE AND OVERVIEW

The goal of military planning is to find the most effective means to reach a desired end state, as defined by the combatant commander. The commander may declare certain milestones from which to gauge success, such as the accomplishment of a certain set of missions. The operational planner must then turn the commander's guidance into an operation plan that specifies the forces, support, and resources required to accomplish the right missions to achieve the combatant commander's goals (JP 1-02, 2001). U.S. Navy Warfare Publication (NWP) 5-01 (2007) specifies a Navy planning process in which the planner identifies the end state and works to fill in the details, such as force employment and support, which will enable mission accomplishment.

United States Fleet Forces Command (FFC) requires a standardized level of planning and execution at the operational level of war. The Maritime Headquarters with Maritime Operations Center (MHQ with MOC) is the instrument through which the operational commander, typically the Combined or Joint Forces Maritime Component Commander (C/JFMCC), employs naval forces for the combatant commander. The MHQ with MOC concept applies to naval component commands, numbered fleets, and principal headquarters commands (FFC, 2007).

The operational commander employs naval forces to accomplish the military objectives of the joint force. Planners decide force allocation during the Concept of Operations (CONOPS) development phase of planning. NWP 5-01 relies on the skill and experience of commanders and planners to design campaigns and efficiently assign forces. The term for this design is "operational art."

Navy planners within the MOC cannot be certain that their practice of operational art results in optimal force employment. There is currently no multi-period operational planning tool able to assign an optimal mix of multiple assets to multiple missions over

multiple regions. Dugan (2007) provides an initial formulation of such a tool; this research continues Dugan's work and expands its capability to generate and evaluate operational plans.

B. BACKGROUND

1. Operational Level of War

MOC planners are focused on the operational level of war, which concerns the planning and execution of major operations and campaigns in order to secure strategic objectives within a theater of operations (JP 1-02, 2001). It follows that the operational level planner must avoid a narrow or tactical point of view. The planner must consider the effects that naval force employment has on joint, combined, or interagency objectives (FFC, 2007).

Zvijac (2008) points out that planning, information, and relationships are critical at the operational level of war. Operational planners must focus on priorities and synchronization rather than on tactics. NWP 5-01 (2007) guides naval planners through this process.

While the operational commander plans and conducts major operations with strategic goals in mind (JP 1-02, 2001), the tactical units themselves actually perform the operations. Figure 1 depicts the relationship between the operational commander and the rest of the chain of command, from the policy level to the tactical level of command.

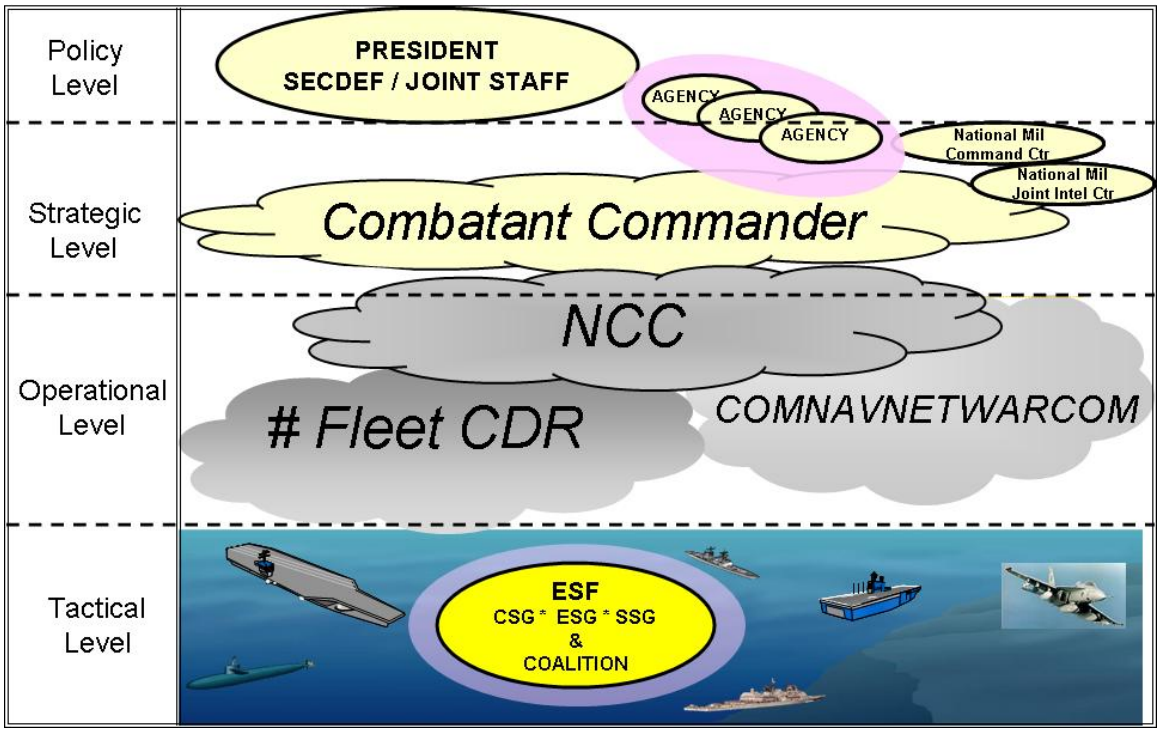

Figure 1. Levels of Command. The operational commander takes direction from the combatant commander at the strategic level of war and directs operations conducted by subordinate forces at the tactical level of war. The naval operational commander is usually the numbered fleet commander or naval component commander (NCC). The NCC, typically the C/JFMCC, touches the strategic level and must be familiar with the strategic goals of the combatant commander and plan operations conducive to accomplishing those goals (From: Slade, 2007).

2. Command and Control Organizational Design

Mission planning is a process through which the planner determines a course of action. The process begins by defining required tasks, assigning resources to accomplish those tasks, and implementing a timeline for completing the tasks (Levchuk et al., 2002). Given the complex nature of planning military operations with limited resources, assigning the optimal mix of forces to the right regions in the theater of operations at the right times is a difficult task.

Levchuk et al., (2002) describe a method to model large organizations and devise mission planning strategies. They seek to achieve an optimal solution to meet mission goals and use resources efficiently. In the context of their research, mission planning

means building the structure of the organization to use its human resources and meet the organization's goals. Their concepts are easily extended to military mission planning—the efficient use of military assets to accomplish the commander's tasking.

Levchuk et al., (2002) present a mathematical model to solve the allocation problem. Their interest as organizational designers is to minimize total mission completion time, i.e., the time to complete all tasks required for the mission. Naval operational planners instead seek to maximize mission accomplishment. Levchuk et al.'s concepts are germane, but their mathematical formulation solves a different problem than the force allocation problem facing the operational commander. Levchuk et al., assign a task (mission) to a platform (ship) and specify a start time (start day). A platform does not perform multiple tasks simultaneously, and task requirements do not change day-by-day. The naval planner needs a multiple period, multiple mission operational model to prioritize and schedule missions, regions, and times.

3. Navy Mission Planner

Dugan (2007) begins development of Navy Mission Planner (NMP), a decision aid to help the C/JFMCC assign forces and missions. NMP is Microsoft Excel-based and exports data to the General Algebraic Modeling System (GAMS, 2009) using the commercial solver CPLEX (2009), to solve the commander's problem. The version of NMP presented here consists of an Excel spreadsheet and Visual Basic macros that store and process scenario data, and an integer linear programming model written in the GAMS algebraic modeling language.

The user interface is an Excel workbook that accepts all user inputs, creates data files in the appropriate format for the GAMS model, and runs GAMS/CPLEX to find the best set of employment schedules for the available assets. The output is a text file containing the optimal ship employment schedules as well as any gaps in mission completions.

Dugan's notional scenario comprises 11 ships and 65 missions in 24 regions. We expand the scenario size to include 18 ships and 80 missions, excluding the aircraft carrier and its escort cruiser, which typically operate independently and support tasking from the Joint Forces Air Component Commander.

C. SCOPE AND OBJECTIVES

The goal of this research is to expand the functionality of NMP and provide a useful tool to the JFMCC planning staff. Dugan's (2007) formulation remains the backbone of NMP; however, the biggest limitation of that is the very small list of possible employment schedules per ship (~5 schedules per ship). We develop a new version of the NMP integer programming model to encompass more employment schedules through constrained enumeration of the feasible region. Total enumeration can produce an unwieldy number of schedules—easily reaching quadrillions of feasible solutions. By constraining the enumeration to eliminate impractical schedules, we significantly reduce the computational burden and still provide useful solutions to the naval planner. We modify the interface and model to handle tens of thousands of employment schedules per ship, leading to much better overall solutions and a much more flexible operational planning tool.

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II. MARITIME MISSION SUPPORT

A. MHQ WITH MOC

1. Introduction

FFC (2007) describes MHQ with MOC as a "rapidly deployable globally networked headquarters." It develops MHQ with MOC because of lessons learned in Operation Enduring Freedom and Operation Iraqi Freedom. Naval operational commands lag behind other services in command and control capabilities and joint planning experience. MHQ with MOC serves to close the gap by standardizing naval operational level commands, properly training and educating personnel, and networking all fleet headquarters commands.

2. MHQ Functional Description

Title 10 United States Code directs the services to man, train, and equip their forces. Operational level naval commands perform these fleet management roles to varying degrees in addition to conducting operations. The MHQ supports both fleet management and operational duties "across the full range of military operations and throughout the maritime environment" (FFC, 2006).

The current MHQ organizes its staff into three functional categories pictured in Figure 2. Dedicated staff elements perform fleet management functions, while personnel assigned to the MOC direct naval and joint maritime operations. The third element of the MHQ is a support staff shared by the fleet management staff and MOC staff. The support staff typically performs administrative, legal, and medical functions (FFC, 2007).

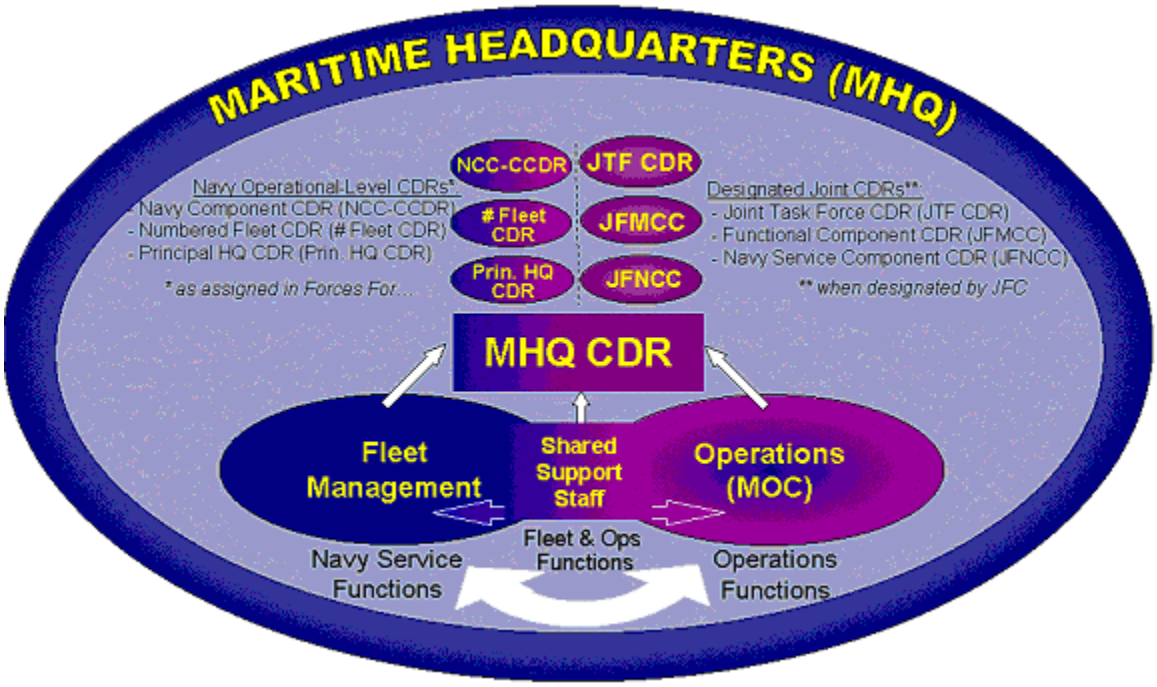

Figure 2. MHQ with MOC Organization. Navy Mission Planner is a planning tool for the operational planner in the Maritime Operations Center. Figure 2 shows the relationship of the MOC within the Maritime Headquarters. MOC is one of three main elements of the MHQ. The others are the fleet management division and support staff. The figure also captures the dual-hat nature of the MHQ commander as a navy operational commander and a joint component commander (From: FFC, 2007).

3. MOC Functions

The MOC is a complex organization and includes all personnel and equipment that support the conduct of naval and joint operations. The MOC organization conforms to the Navy standard staff organization of boards, centers, bureaus, cells, working groups, and teams. The MOC "assess[es], plan[s], and execute[s] operational level missions, including strategic communications, theater security cooperation, intelligence preparation of the environment, and maritime security operations" (FFC, 2007). MOC takes on numerous roles to accomplish these missions. In addition to directing operations, the MOC establishes a chain of command for and delegates command authority to subordinate commanders.

4. Operational Control

Navy Warfare Development Command TACMEMO 3-32-06, Combined/Joint Force Maritime Component Commander (C/JFMCC) Planning and Execution (NWDC, 2006) provides guidance to operational commanders. NWDC (2006) defines operational control (OPCON) as:

> command authority exercised by commanders at any echelon at or below the level of COCOM [combatant command] and can be delegated. OPCON is inherent in COCOM and is the authority to perform those functions of command over subordinate forces involving organizing and employing commands and forces, assigning tasks, designating objectives, and giving authoritative direction necessary to accomplish the mission.

The combatant commander usually delegates OPCON to the operational commander. OPCON differs from tactical control (TACON) in that TACON is short-term local direction specific to an assigned task or mission. While the MHQ normally retains OPCON, it typically delegates TACON to subordinate commanders.

5. Planning in MHQ with MOC

The Future Plans cell is responsible for developing long-term plans and orders. Future Operations takes responsibility for these plans as the time for execution grows nearer. The Future Operations cell sets mission priorities and allocates available forces to the missions (FFC, 2007).

NWP 5-01 (2007) lists a detailed series of actions known as the Navy planning process in which the Future Plans and Future Operations cells produce the operation plans and orders. The process includes mission analysis, friendly and enemy course of action development, wargaming the options, and preparing the operation order. During course of action development, the operational planners complete worksheets, provided in NWP 5-01, to sketch out all aspects of the plan, to include force allocation.

The task of completing the NWP worksheets, i.e., assigning missions to forces in specific regions at specific times, is a manual process. Commander, U.S. Third Fleet Plans Directorate, specifically the Time-Phased Force Deployment Data and Joint Operation Planning and Execution System cell (Sironi, 2009), confirms this process.

Whiteboards and spreadsheets can assist the process of completing the worksheets, but planners manually insert forces to fill requirements. As requirements change, the planners rearrange their allocations.

There is no planning tool with an algorithm to optimize ship employment schedules. Some planning aids pull data from various sources to improve the display of information needed to craft the schedules (Sironi, 2009). According to Future Schedules Officers from the Third Fleet Operations Directorate (Baecker, 2009), other tools ensure that the ships in theater meet COCOM capability and presence requirements while observing the Chief of Naval Operations standards for operations tempo. None of the tools produce an optimal employment schedule by ship, mission, region, and day.

Figure 3 shows current MHQs under their respective combatant commanders. Note that in the current configuration, Military Sealift Command and Naval Special Warfare Command are MHQs without a MOC.

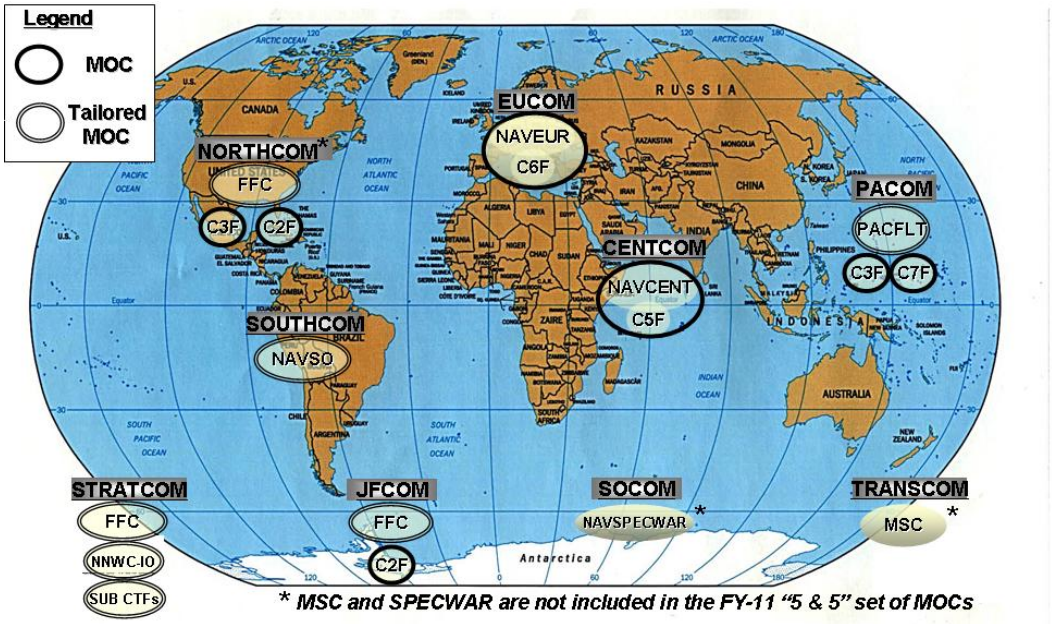

Figure 3. U.S. MHQ and MOC Commands. U.S. Fleet Forces Command considers the Navy component commanders, force commanders, and joint force maritime component commanders to be Maritime Headquarters. Each contains a Maritime Operations Center. Some MOC responsibilities vary according to requirements in the area of operations. These are tailored MOCs. For example, Commander, U.S. Pacific Fleet (PACFLT) is a tailored MOC, but Commander, U.S. Third Fleet (C3F) is a standard MOC (From: Slade, 2007).

B. FLEET FORCES COMMAND VISION FOR MHQ WITH MOC

1. End State

The U.S. Navy intends to be more than just a force-provider. FFC (2007) envisions a MHQ with MOC built for centralized command, distributed planning, and decentralized execution. Naval staffs have tended to take tactical views of operations, but MOC planners take operational views. The result is a MHQ fulfilling the role of a true operational commander providing full support to joint operations worldwide.

2. Transformation

Full implementation of MOC requires change within the operational level staffs. FFC (2007) notes that naval staffs must further integrate into the joint planning process, standardize staff functions, ensure joint professional education for personnel, implement a certification and training process, and improve the staff planning process. Further, MHQs without a MOC operate mainly to provide fleet management functions. These MHQs treat operations functions as collateral duties.

The non-MOC MHQ staffs are challenged to efficiently shift roles between fleet management and operational duties. MOC provides a common organization dedicated to the operational role. Full implementation of an independent but linked MOC ensures greater staff efficiency, especially as operational commitments increase without a reduction in fleet management requirements (FFC, 2006).

NMP stands to facilitate the improvement of the MOC planning process. Dugan (2007) notes that assigning assets to missions and regions over the planning horizon is "time consuming and difficult." NMP provides value to the MOC staff and allows for improving the staff planning process. NMP provides tens of thousands of courses of action, evaluates each one, and recommends the best solution by maximizing the value of assigned missions to create an optimal force mix.

Chapter III develops full NMP model specifications and inputs.

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III. NMP OPTIMIZED MODEL WITH ENUMERATION

A. DESCRIPTION

NMP uses an integer linear program to compute the optimal employment schedule for each U.S. Navy combatant ship assigned to a particular area of operations. This research updates Dugan's (2007) original formulation and adds automatic schedule generation capability. The operational planner's inputs to NMP remain largely unchanged; therefore, the following discussion relies heavily on Dugan's original description.

The planner's initial NMP input is the set of *days* covering a finite planning horizon. The user then inputs the planned operating areas into NMP as *regions*, each of which is an area of the ocean specified by a latitude and longitude at or near its center. We modify Dugan's (2007) concept of a set of regions from a grid of rectangular regions to a connected network of nodes. The node concept provides the planner with flexibility to input desired areas of operation and to easily determine the shortest travel times between regions. (Note that the definition of a region does not restrict a ship to operating on one point in the water; individual units are free to maneuver as necessary around the region to accomplish the assigned mission.)

The user then defines adjacency *arcs*, representing unobstructed great-circle navigation routes between pairs of regions. NMP then computes and stores the arc lengths (in nautical miles), the shortest path between all regions in nautical miles using sequences of great circle arcs, and transit days (at 16 knots) required for each such path.

Mission requirements are specified in a list of *missions*, each of which has a *mission type*, drawn from a fixed list of types (e.g., air defense, surface warfare, etc., as defined in Chapter IV), a region, and a set of days for which it is required. In addition to the type, region, and day requirements, the planner defines, for each mission, in each region, on each day, a *value* for accomplishing that mission, and a set of *mission dependencies*, which define prerequisite missions that must be accomplished simultaneously with that mission, to enable other ships to complete it.

The last input set is the set of available *ships*. The operational planner defines the set of ships by hull number and name, start day, start region, and available *concurrent mission capability sets* (*CMCs*). The start day is the first day of the planning horizon during which a ship is able to complete mission tasking. A single CMC set is a vector of *accomplishment* values, one for each mission type, that indicate the fraction of a particular mission that a ship can accomplish concurrently with other missions in the CMC set. One ship can have multiple CMC sets to choose from, but it can only operate under one CMC on any given day. Values less than one indicate reductions in readiness for various issues, such as maintenance or personnel.

The output from NMP is a set of *employment schedules*. Each ship's employment schedule specifies, for each day in the planning horizon, the region in which the ship operates and the assigned CMC set for that ship on that day in that region. NMP provides employment schedules to maximize the aggregate value of all maritime missions accomplished over the planning horizon (Dugan, 2007).

B. LIMITATIONS AND ASSUMPTIONS

NMP limits the planning horizon to fifteen day windows due to operational limitations on ship employment schedules. One can model a full campaign by solving for a series of fifteen day windows using a "rolling horizon" approach.

NMP calculates transit time based on a 16-knot speed of advance and rounds fractional transit time to represent whole days. NMP rounds days down when the fractional element is less than eight hours. It rounds up when the fraction is greater than or equal to eight hours. In other words, NMP assumes that a unit may participate in missions if it arrives on station with at least two-thirds of a day remaining.

C. NMP INTEGER PROGRAM FORMULATION

Many of the inputs to NMP are unchanged, but this research significantly changes the formulation of model. The following integer linear program solves for the optimal set of Navy ship employment schedules.

1. Sets and Indices [cardinality]

$s \in S$ Ship (hull number and name, alias s') [~50]

$m \in M$ Mission type (alias m') [~10]

(e.g., AD, MIO, Intel, TBMD)

$c \in C_s$ Concurrent mission capability set for ship *s* [~10]

$m \in M_c$ Mission types in concurrent (simultaneous) mission set *c*

(e.g., ship *s* can simultaneously perform mission type *m* in concurrent mission capability set *c*.

$p \in P$ Employment schedules [~1 million]

$p \in P_s \subseteq P$ Employment schedules for ship *s* [~1 million]

($\bigcup_s P_s \equiv P$, P_s is a partition of *P*.)

$s(p)$ Ship of employment schedule *p*

$r \in R$ Regions in AOR [~30]

$d \in D$ Days in planning horizon (alias d', d'') [~14]

$r(p,d)$ Region employment schedule *p* visits on day *d*

$n \in N$ Ordinal for multiple missions of the same mission type [~5]

(E.g., several ships may conduct ASW at the same time within the same region, but with different effectiveness.

2. Data [units]

$value_{m,n,r,d}$ Priority of *n*-th mission of type *m*, in region *r* on day *d* [1-20] [value]

($\{m,n,r,d\} \in MNRD$ tuples exist only for non-zero values)

$accomplish_{c,m}$ Level of accomplishment of concurrent mission set $c \in C_s$, mission $m \in M_c$ [0.0-1.0] (Note that each ship may have its own set of concurrent mission capability sets, and that some of these sets may contain the same missions, but with different accomplish rates to represent the ship choosing to change emphasis between missions.)

3. Induced Index Sets

$\{m,n,r,d\} \in MNRD$ 4-tuple exists only if $value_{m,n,r,d} > 0$ or $accomplish_{s,m} > 0$ for some ship that can employ a concurrent mission capability set that includes mission *m* in region *r* on day *d*

$\{m,r,d\} \in MRD$ 3-tuple exists only if $\{m,n,r,d\} \in MNRD$ does for some *n*

$\{m,r,d,m'\} \in MRDM$ 4-tuple exists if, in region *r* on day *d*, mission *m* can be undertaken only if mission m' is fully accomplished

4. Variables [units]

$U_{m,n,r,d}$ Level of accomplishment of the *n*-th mission type *m* assignment in region *r* on day *d* [0.0-1.0]

$V_{m,r,d}$ =1 if mission *m* is fully accomplished in region *r* on day *d* [binary]

$W_{s,c,d,r}$ =1 if ship *s* employs concurrent mission capability *c* on day *d* in region *r* [binary]

$X_{s,s',r,d}$ =1 only if ships *s* and s' are both in region *r* on day *d* [binary]

Y_p =1 if schedule *p* is selected [binary]

5. Formulation

$$\max \sum_{\{m,n,r,d\} \in MNRD} value_{m,n,r,d} U_{m,n,r,d} \qquad \text{(T0)}$$

s.t. $\sum_{p \in P_s} Y_p = 1 \qquad \forall s \in S \qquad (T1)$

$\sum_{c \in C_s} W_{s,c,d,r} \le \sum_{\substack{p \in P_s \\ \wedge \exists r(p,d)}} Y_p \qquad \forall s \in CS, d \in D, r \in R \quad (T2)$

$\sum_{n \mid \{m,n,r,d\} \in MNRD} U_{m,n,r,d} \le \sum_{s,c \in C_s} accomplish_{c,m} W_{s,c,d,r}$

$\forall \{m,r,d\} \in MRD \qquad (T3)$

$V_{m,r,d} \le \sum_{\substack{p \in P \| r = r(p,d) \\ \wedge c \in C_{s(p)} \wedge m \in M_c}} accomplish_{c,m} Y_p \qquad \forall \{m,r,d\} \in MRD \qquad (T4)$

$V_{m,r,d} \le \sum_{n \mid \{m,n,r,d\} \in MNRD} U_{m,n,r,d} \qquad \forall \{m,r,d\} \in MRD \qquad (T4a)$

$U_{m,n,r,d} \le V_{m',r,d} \qquad \forall m,n,r,d \mid \{m,n,r,d\} \in MNRD$
$\wedge \{m,r,d,m'\} \in MRDM \qquad (T5)$

$U_{m,n,r,d} \in [0,1] \qquad \forall \{m,n,r,d\} \in MNRD$

$V_{m,r,d} \in \{0,1\} \qquad \forall \{m,r,d\} \in MRD$

$W_{s,c,d,r} \in \{0,1\} \qquad \forall s \in S, c \in C_s, d \in D, r \in R$

$Y_p \in \{0,1\} \qquad \forall p \in P \qquad (T6)$

6. Discussion

The objective (T0) sums the total value of completed and partially completed missions. Each packing constraint (T1) allows exactly one employment schedule per ship. Each constraint (T2) permits a combatant to employ a concurrent mission capability on a given day only if an employment schedule exists for that ship. Each constraint (T3) limits the sum of the partial completion values of all missions by the total mission accomplishment for every tuple of mission, region, and day. Each constraint (T4) assigns full accomplishment to a mission in a particular region on a particular day only if there is at least one total unit of accomplishment for that same combination of

mission, region, and day. Similarly, each constraint (T4a) assigns full accomplishment to a mission in a particular region on a particular day only if each mission copy combines in that region on that day to produce at least one total unit of accomplishment. Constraints T4 and T4a are equivalent for determining optimal employment schedules, Y, but T4a enforces additional structure on the individual mission accomplishment variables, U, for prerequisite missions that have no prescribed value. Each constraint (T5) ensures that no mission accrues accomplishment in a given region on a given day unless each of its prerequisite missions (if any) in that region on that day has full accomplishment. (T6) defines the variable domains.

D. CONSTRAINED ENUMERATION

1. General

NMP builds candidate employment schedules, i.e., the values for $r(p,d)$ for all p and d, through constrained enumeration. Total enumeration of all possible ship positions over each day in the planning horizon runs in exponential time and could produce an enormous number (e.g., for just ten regions over fifteen days, we have on the order of 10^{15} feasible schedules per ship) of schedules. This result is impractical for many reasons, including unacceptably long runtime and system memory limitations. NMP limits the enumeration of schedules through various user-defined parameters.

Our implementation of a path enumeration algorithm avoids recursive programming by explicitly maintaining a stack of regions comprising a current partial path, and arrays that hold path data during the enumeration computations. The stack provides memory for the nodes on the current path. The top node on the stack becomes the source node for the enumeration of the remaining path completions. The arrays hold data for the positions of nodes on the current path, the forward-star structure, the list of outbound arcs from the node, and the next candidate arc in the forward-star (Carlyle, 2008).

2. Path Enumeration in NMP

Path enumeration in NMP begins by reading the user-defined limits on the number of ship schedules, *max schedules* and *max schedules per ship*, and the number of stall days, *max stall days per ship*. A stall day is a day in which a ship remains in the same region it occupied the previous day. The parameter *max schedules* is the main limit. When the number of schedules reaches this constraint, the enumeration terminates. Reducing the maximum allowable stall days permits NMP to consider a more diverse set of schedules within the number of maximum schedules. Conversely, increasing maximum stall days reduces diversity, but allows a single ship to stay on one long mission without rotating out.

This algorithm uses two stacks and six arrays. One stack (the region stack) holds incumbent path nodes, and the other (the next-region stack) points to candidate nodes. The arrays hold more data useful to the enumeration process. One flags each ship having a complete schedule. Two maintain ship employment schedules—one maintains daily resolution on covered regions and the other maintains regional assignments by ship. The fourth and fifth arrays store the start day and start region, respectively, for each ship. The last array counts the consecutive stationary days within a candidate schedule. This array ensures compliance with the constraint max stall days.

NMP treats the set of regions as a network, with user-defined arcs connecting the nodes (the regions themselves) along great-circle navigable routes. The source node is the planner input *start region*. NMP reads and stores the distances between regions, transforms the distances into transit days, and creates a new array to store this information.

With these administrative processes complete, NMP begins the actual task of building feasible schedules. The process entails a series of loops. The outer loop iterates through the list of ships.

Within the main outer loop, the second loop occurs while three conditions are true. The stack pointer, i.e., the current day of the incumbent schedule, must be greater

than or equal to the ship's start day. The second and third continuation conditions are that the number of schedules generated meets the constraints on total schedules generated and schedules generated per ship.

A third loop then begins and performs a depth-first search of remaining regions while the number of schedules generated meets the two schedule constraints. NMP considers all other nodes as candidates for the path until the last day of the planning horizon. NMP then starts building all possible directed paths, thought of as one way routes between regions, from source to sink by building a series of partial paths. At the end of an incumbent path, NMP enumerates all remaining completions of the path.

NMP considers leaving the ship in the current region if the ship has stall days remaining. If not, then NMP looks to the next region for a suitable mission for the given ship. If there is a feasible mission, then NMP adds the region to the next region stack.

Next, NMP compares the distance between the current and next regions. If the distance does not allow for transit in a single day, then the ship is unavailable until completion of the transit period.

At the final day of the planning horizon, NMP reaches the end of the depth-first search. It continues the enumeration loop until it has built every feasible schedule or has reached the maximum number of schedules.

IV. ANALYSIS OF RESULTS

A. SCENARIO

1. Mission Types

Dugan (2007) applies ten mission types and two supporting mission types in NMP. We modify the NMP mission set to include eleven mission types and delete the supporting mission types Transit and Off-Station. NMP handles transit and off-station time within the underlying VBA code.

While representative of the most common maritime missions, our list of mission types is not intended to be exhaustive. The operational planner may define any mission type necessary to suit the commander's objectives. NMP accepts any mission name on the *Missions* worksheet.

Acronyms or abbreviations in parenthesis denote NMP notation. Joint Publication 1-02 (2001) defines the following, except as otherwise noted:

a. Air Defense (AD)

> Defensive measures designed to destroy attacking enemy aircraft or missiles in the atmosphere, or to nullify or reduce the effectiveness of such attack. (JP 1-02, 2001)

We consider air defense separately from missile defense.

b. Theater Ballistic Missile Defense (TBMD)

A ballistic missile is:

> any missile which does not rely upon aerodynamic surfaces to produce lift and consequently follows a ballistic trajectory when thrust is terminated. (JP 1-02, 2001)

Missile defense is:

> defensive measures designed to destroy attacking enemy missiles, or to nullify or reduce the effectiveness of such attack. (JP 1-02, 2001)

We use the term TBMD to describe the naval mission of providing ballistic missile defense to a theater of operations.

c. Antisubmarine Warfare (ASW)

Operations conducted with the intention of denying the enemy the effective use of submarines. (JP 1-02, 2001)

d. Surface Warfare (SUW)

That portion of maritime warfare in which operations are conducted to destroy or neutralize enemy naval surface forces and merchant vessels. (JP 1-02, 2001)

e. Strike

An attack to damage or destroy an objective or a capability. (JP 1-02, 2001)

Naval fire resources are sea based or sea supported, and include Navy and Marine Corps lethal and nonlethal air-delivered weapons, maritime-based gunfire and land-attack missiles, and maritime-based naval special warfare units. (NWP 3-09.1, 2005)

f. Naval Surface Fire Support (NSFS)

Fire provided by Navy surface gun and missile systems in support of a unit or units. (JP 1-02, 2001)

g. Maritime Interception Operations (MIO)

Efforts to monitor, query, and board merchant vessels in international waters to enforce sanctions against other nations such as those in support of United Nations Security Council Resolutions and/or prevent the transport of restricted goods. (JP 1-02, 2001)

h. Mine Countermeasures (MCM)

All methods for preventing or reducing damage or danger from mines. (JP 1-02, 2001)

i. Mine Warfare (Mine)

The strategic, operational, and tactical use of mines and mine countermeasures. Mine warfare is divided into two basic subdivisions: the laying of mines to degrade the enemy's capabilities to wage land, air, and

maritime warfare; and the countering of enemy-laid mines to permit friendly maneuver or use of selected land or sea areas. (JP 1-02, 2001)

j. Intelligence Collection (Intel)

The collection of available information concerning foreign nations, hostile or potentially hostile forces or elements, or areas of actual or potential operations. (JP 1-02, 2001)

k. Submarine Intelligence Collection (SubIntel)

The previous ten mission types are also used in Dugan (2007). We have added SubIntel, a user-defined mission, to illustrate the flexibility of this planning tool through its ability to adapt to *any* list of mission types. We define SubIntel as an intelligence collection mission that can only be performed by a submarine.

2. Theater of Operations

The unclassified scenario considers a notional series of events on the Korean peninsula leading to U.S. and South Korean Combined Forces Command action in the region. U.S. Pacific Command orders naval assets to the region, beginning with forward deployed forces and surging additional assets from outside the theater. Figure 4 shows the area of operations surrounding the Korean Peninsula divided into 16 regions. The vertical gridlines depict degrees of east longitude, and the horizontal gridlines depict degrees of north latitude. Appendix A contains the NMP Region worksheet in which we define the regions and arcs for our scenario.

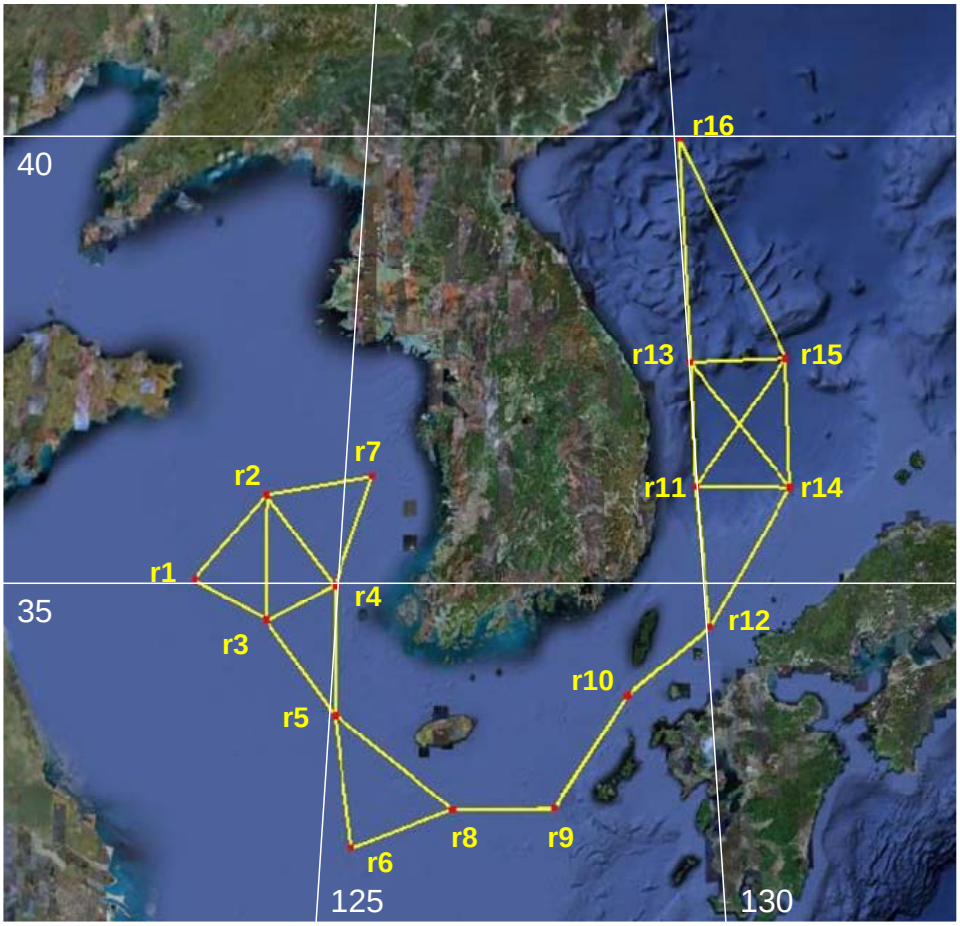

Figure 4. Scenario Region. The notional scenario takes place in the waters surrounding the Korean Peninsula. The horizontal gridlines represent degrees of north latitude. Vertical gridlines represent degrees of east longitude. Each gridline is approximate, and longitudinal lines appear to slope due to the simple cylindrical projection of the map. 16 regions, or waypoints, depict the area of operations. Regions and the arcs connecting them are user-defined inputs to Navy Mission Planner (Adapted From: Google Earth, 2009).

3. Resources

The surge ships arrive in theater sequentially. Due to the rapidly escalating situation, not all forces are on station when hostilities commence. Table 1 depicts the ship input to NMP used in this scenario as well as an additional, unused ship, which demonstrates the use of the Available column. Appendix B shows the entire ship set, including all ships not used in the scenario.

From this, one can discern the flow into theater. Notionally, two cruisers, four destroyers, and two fast-attack submarines are forward deployed and available on day one of the fifteen-day planning horizon. On day four, a surface action group consisting of a cruiser, three destroyers, and two frigates arrive on station. On day six, the third fast-attack submarine arrives at region r7. Finally, on day seven, the last units arrive. These are a cruiser, destroyer, and frigate.

Table 1. NMP Ship Resources. The user inputs available ships by hull number, name, availability, ship class, type, start day, start region, and available CMCs. For example, USS Kidd, DDG 100 is available for tasking on day four and begins in region r5. CMCs C13, C16, and C19 are available to Kidd. Note also that CG 63, USS Cowpens, is not available for this scenario.

Ship	Name	Avail	Class	Type	Start Day	Start Region	CMCs		
CG61	Monterey	x	CG	COMBAT	1	r2	C1	C5	C7
CG66	Hue City	x	CG	COMBAT	1	r13	C2	C5	C8
CG72	Vella Gulf	x	CG	COMBAT	4	r7	C3	C6	C9
CG58	Philippine Sea	x	CG	COMBAT	7	r10	C4	C5	C10
CG63	Cowpens		CG	COMBAT					
DDG53	John Paul Jones	x	DDG	COMBAT	1	r1	C11	C15	C17
DDG54	Curtis Wilbur	x	DDG	COMBAT	1	r4	C11	C15	C17
DDG86	Shoup	x	DDG	COMBAT	1	r9	C12	C15	C18
DDG90	Chaffee	x	DDG	COMBAT	1	r7	C12	C15	C18
DDG100	Kidd	x	DDG	COMBAT	4	r5	C13	C16	C19
DDG80	Roosevelt	x	DDG	COMBAT	4	r13	C11	C15	C17
DDG104	Sterett	x	DDG	COMBAT	4	r4	C11	C15	C17
DDG97	Halsey	x	DDG	COMBAT	7	r11	C11	C15	C17
FFG48	Vandegrift	x	FFG	COMBAT	4	r10	C21	C25	
FFG52	Carr	x	FFG	COMBAT	4	r11	C22	C25	
FFG47	Nicholas	x	FFG	COMBAT	7	r8	C23	C26	
SSN752	Pasadena	x	SSN	COMBAT	1	r12	C31	C37	
SSN718	Honolulu	x	SSN	COMBAT	6	r7	C34	C37	
SSN717	Olympia	x	SSN	COMBAT	1	r16	C33	C37	

Table 2 shows an example CMC list for the cruiser ship class. Appendix C shows the entire CMC matrix for our scenario. C1 is the full concurrent mission capability for a cruiser's core missions of AD, ASW, SUW, Strike, and NSFS. C2, C3, and C4 depict examples of degradations from C1 in which full capability is unavailable for some missions. C5 and C6 are options for MIO. One may interpret C5 as the base case in which the staff planner chooses not to assign a cruiser with TBMD, ASW, or NSFS when that cruiser is assigned a MIO mission. C6 is similar to C5, but it provides a degraded

capability in SUW. C7, C8, C9 and C10 are options for TBMD in which AD is zero. C8 through C10 are examples of degraded concurrent capabilities for TBMD. The operational planner is free to modify the CMC matrix to fit any necessary combination of capabilities and casualties. The standard, full mission capable CMCs for a cruiser are C1, C5, and C7. The majority of ships listed in Table 1 are operating with degraded mission capabilities.

Table 2. CMC Matrix for CG Class of Ships. CMC matrix is a user-defined input. The operational planner keeps track of ships' system status and adjusts the matrix accordingly. For example, C1 shows that a cruiser can complete AD, ASW, SUW, Strike, NSFS, and Intel concurrently and to 100% completion. C2 shows a situation in which a ship has casualties or shortfalls affecting its ability to perform ASW and NSFS, which can only be accomplished at 50% and 75% of normal effectiveness, respectively. Note that the planner should not assign C1 if a ship has mission degradations C2, C3, or C4.

		Mission										
Ship Class	CMC	AD	TBMD	ASW	SUW	Strike	NSFS	MIO	MCM	Mine	Intel	SubIntel
CG	C1	1	0	1	1	1	1	0	0	0	1	0
	C2	1	0	0.5	1	1	0.75	0	0	0	1	0
	C3	1	0	1	0.5	1	0.5	0	0	0	1	0
	C4	1	0	0	1	1	1	0	0	0	1	0
	C5	1	0	0	1	1	0	1	0	0	1	0
	C6	1	0	0	0.5	1	0	1	0	0	1	0
	C7	0	1	1	1	1	1	0	0	0	1	0
	C8	0	1	0.5	1	1	0.75	0	0	0	1	0
	C9	0	1	1	0.5	1	0.5	0	0	0	1	0
	C10	0	1	0	1	1	1	0	0	0	1	0

4. Priorities and Requirements

Day one represents the start of the deterrence phase of joint operations, Phase I (JP 3-0, 2006), during which naval units perform AD, TBMD, ASW, MIO, and intelligence collection. In Phase I the ships patrol regions prioritized in four groups. TBMD in region r2, ASW in r12, and SubIntel in r16 are highest priorities. Regions r1, r7, and r13 are next priority as these are the extreme western and northern regions. Regions r4, r9, and r11 are third priority because r4 and r11 are the second most northern regions and r9 closes the ring around the peninsula. The remaining regions are lowest priority.

Mission values reflect these priorities. Region r2 is the designated TBMD sector. Region r12 is a chokepoint facilitating north/south and east/west flow. Enemy submarines are the chief threat in this region, and ASW is the top priority here. Region r16, in international waters, provides a northern vantage point for intelligence collection. To ensure these missions are fully covered, we assign value 20. We assign values to MIO, AD, ASW, and Intel according to regional priorities. The missions in the second priority regions have values 9, 7, 8, and 7 respectively. The values reduce by two for each lower priority.

On day five, Phase II operations to seize the initiative begin (JP 3-0, 2006). Phase II is the de facto commencement of offensive operations. Required missions include SUW, Strike, and NSFS in addition to those begun on day one. Phase II runs through the end of the scenario, day fifteen. TBMD in region r2, ASW in region r12, and SubIntel in region r16 remain the top priority as in Phase I. Regions r5, r7, and r13 are next priority, followed by regions r4, r10, and r11, then regions r8 and r9. The reasoning for the prioritization of regions follows similar logic to the process of Phase I. Strike missions in regions r5, r7, and r13 are the highest remaining priority and take a value of 15. Values for NSFS, SUW, MIO, and ASW begin at 9, 7, 7, 5, and 5 respectively. Values again reduce by two for each succeeding priority level. Appendix D contains the entire mission set for our scenario. Table 3 shows a portion of this set for the first five scenario regions.

Table 3. NMP Missions Input. Required mission type, region, time horizon, value, and prerequisite missions are input via the Mission worksheet of NMP. This table shows missions for the first five regions. For example, TBMD in region r2 appears for all 15 scenario days and has a value of 20. AD is a prerequisite mission for TBMD, but is not explicitly scheduled for the initial run.

Mission	Include	Type	Region	Start Day	End Day	Value	Requires	
m1	x	MIO	r1	1	4	9	AD	
m2	x	AD	r1	1	4	7		
m3	x	ASW	r1	1	4	8	AD	SUW
m4	x	Intel	r1	1	4	7		
m5	x	TBMD	r2	1	15	20	AD	
m6	x	MIO	r3	1	4	5	AD	
m7	x	AD	r3	1	15	3		
m8	x	ASW	r3	1	4	4	AD	
m9	x	Intel	r3	1	15	3		
m10	x	MIO	r4	1	4	7	AD	
m11	x	AD	r4	1	15	5		
m12	x	ASW	r4	1	4	6	SUW	
m13	x	Intel	r4	1	15	5		
m14	x	Strike	r4	5	11	7	AD	
m15	x	NSFS	r4	5	8	5	AD	
m16	x	SUW	r4	5	11	5	AD	
m17	x	MIO	r4	12	15	3	AD	
m18	x	ASW	r4	12	15	3	SUW	
m19	x	MIO	r5	1	4	5	AD	
m20	x	AD	r5	1	15	3		
m21	x	ASW	r5	1	4	4	SUW	
m22	x	Intel	r5	1	15	3		
m23	x	Strike	r5	5	11	15	AD	
m24	x	NSFS	r5	5	8	7	AD	
m25	x	SUW	r5	5	11	7	AD	
m26	x	MIO	r5	12	15	5	AD	
m27	x	ASW	r5	12	15	5	SUW	

B. RESULTS

This research investigates four runs of the scenario. We explore methods the operational planner may use to improve the results NMP provides. Each run uses a maximum of 750,000 total schedules and 75,000 maximum schedules per ship.

1. Initial Run

We first run the model using a value for max stall days of three days. We achieve a total mission value of 2416.50, with an upper bound of 2535.50. Scanning the output, we check for completions of missions with prerequisites. If any prerequisite mission is not accomplished, then there is a gap in accomplishment of the main mission as well. For

example, Appendix D lists missions m3, m12, and m21 as ASW missions with an SUW prerequisite mission. As the operators in this scenario, we do not assign a SUW mission for the first four scenario days. As a result, these ASW missions are gapped, except on day four in region r5. On this day, DDG 100 and DDG 54 perform SUW, allowing completion of mission m21, ASW. This result is shown in Table 4. Note that the SUW mission accrues no value, because it is not a user-assigned mission for that region or day.

Knowing that the maritime commander is most interested in the highest priority missions, we track the completion of these. We see that the high-priority TBMD mission takes place only on day fifteen. While TBMD in region r2 has a value of 20 and is one of the three highest priority missions, there is not enough air defense support. AD is a prerequisite mission, but it is not explicitly assigned in the Missions worksheet; therefore, it would accrue no value. NMP can find more value in other, lower-valued missions rather than assigning transit days to move a second asset to region r2 and perform zero-value AD.

The second high-priority mission, ASW in region r12, is gapped on days four through six. On seven of the nine succeeding days, it only accrues half-value. With limited resources, a ship degraded in ASW must perform the mission.

NMP gaps the SubIntel mission on ten of the fifteen days in the scenario. SSN 717 begins the scenario in r16 and performs the SubIntel mission for the first three days. Once the max stall days limit is reached, it moves on. Due to the long transit distance, NMP assigns no other sub until day nine, for one day only, then again until day fifteen.

Table 4. Selected Mission Accomplishments. This table displays selected mission accomplishment output. The column Value is the user-assigned value for the mission. Effort is the decision variable U, the level of accomplishment for that mission in that region on that day. The column Achieved is the portion of the objective value achieved by accomplishing the given mission in the given region on the given day and is the product of Value and Effort. For example, on day four in region five, mission SUW has no value, but is performed fully, that is to a level of one. The column Achieve is zero, and there is no contribution to objective value. This prerequisite mission allows completion of ASW on day four in region five, with a value of four, effort of one, and achieved value of four.

MISSION ACCOMPLISHMENT					
Region	**Mission**	**Day**	**Value**	**Effort**	**Achieved**
r1	ASW	d4	8	0	0
r4	ASW	d4	6	0	0
r5	SUW	d4	0	1	0
r5	ASW	d4	4	1	4
r2	AD	d1	0	1	0
r2	AD	d15	0	1	0
r2	TBMD	d15	20	1	20
r12	ASW	d4	20	0	0
r12	ASW	d5	20	0	0
r12	ASW	d6	20	0	0
r16	SubIntel	d1	20	0	0
r16	SubIntel	d2	20	0	0
r16	SubIntel	d3	20	0	0
r16	SubIntel	d9	20	0	0
r16	SubIntel	d15	20	0	0

2. Second Run—Assign AD in Region r2

The operational commander's first reaction to hearing that TBMD, one of the number-one priority missions, is gapped for fourteen days would be to order assets moved to that region to do the mission. For the second run, two changes are made to the scenario. First, as shown in Table 5, the user schedules AD in region r2 for the duration of the planning horizon. Note that the value is 20, commensurate with the value of the TBMD mission.

Table 5. Example of Ensuring High Priority Prerequisite Missions. AD is a prerequisite mission for TBMD in region r2 for each day in the planning horizon. In the original scenario, the operational planner does not schedule the AD mission. The planner lets NMP decide if there is more value in assigning an AD asset to the high-priority TBMD mission, or to assigning the two assets elsewhere. By adding a dedicated requirement for AD in region r2 and valuing it according to the value of TBMD, in this case 20, the planner attempts to ensure that NMP schedules the commander's highest priority mission.

Mission	Include	Type	Region	Start Day	End Day	Value	Requires	
m80	x	AD	r2	1	15	20		

The second change is illustrated in Table 6, which shows the assignment of DDG 54 to region r2 on day one of the planning horizon. This change assigns a second asset to the region in order to meet mission requirements.

Table 6. Example of Assigning a Ship to the Region Corresponding to a High Priority Prerequisite Mission. In the original scenario, DDG 54 begins in region r4. For the second and succeeding runs, DDG 54 begins in region r2. There are now two assets assigned to begin operations in region r2, corresponding to two mission requirements.

Ship	Name	Avail	Class	Type	Start Day	Start Region	CMCs		
DDG54	Curtis Wilbur	x	DDG	COMBAT	1	r2	C11	C15	C17

The results of these changes are mixed. Objective value improves to 2737.00, with an upper bound of 2749.67. The prerequisite for TBMD, AD, is scheduled for the entire planning horizon. TBMD appears for the first three days, but the enumeration limit on max stall days forces the ships to move from region r2. DDG 53 moves into the region to perform AD, but a second asset is not available to perform TBMD. TBMD is gapped from day four until it resumes for days 14 and 15.

The ASW mission in region r12 and the SubIntel mission in region r16 are unchanged. The ASW gap remains on days four, five, and six, and SubIntel again takes place only on days one through three, nine, and fifteen.

3. Third Run—Extend *Max Stall Days* to Seven

The second run gives us an improvement over the first in that NMP fully schedules AD in region r2. There is an assignment shortfall, however, because the max

stall days constraint forces ships out of not only the highest priority regions where the highest priority missions occur, but out of all regions after three days. The third run extends max stall days to seven in an attempt to improve mission completion values.

In the third run, objective value again improves to 2940.00, with an upper bound of 2961.00. AD in region r2 occurs each day of the planning horizon. The TBMD assignment is improved compared to the second run. TBMD occurs for the first seven days, and then it is gapped for the next four. TBMD is again scheduled in region r2 for days twelve through fifteen. Again NMP allows CG 61 and DDG 54 to maintain station until the expiration of the max stall days, at which time there is a four day gap until two assets are available in region r2.

DDG 53 moves into region r2 on day five, after completing the AD, MIO, and Intel requirements in region r1 for the first four days. NMP determines that this is the ship to take over AD in region r2 on day eight. DDG 53 has no better mission within transit range of region r1 for days five through seven, so it moves into region r2 early, meaning three assets are in that region covering the two missions. Table 7 illustrates the mission accomplishment for TBMD and AD in region r2.

Table 7. Air Defense and TBMD Mission Accomplishments in Region r2. AD and TBMD take place in region r2 for the first seven days of the scenario. Once the constraint max stall days is reached, the assigned ships move on to other regions. We see that while AD is covered every day, TBMD has a four day gap beginning on day eight.

MISSION ACCOMPLISHMENT					
Region	**Mission**	**Day**	**Value**	**Effort**	**Achieved**
r2	AD	d1	20	1	20
r2	AD	d2	20	1	20
r2	AD	d3	20	1	20
r2	AD	d4	20	1	20
r2	AD	d5	20	1	20
r2	AD	d6	20	1	20
r2	AD	d7	20	1	20
r2	AD	d8	20	1	20
r2	AD	d9	20	1	20
r2	AD	d10	20	1	20
r2	AD	d11	20	1	20
r2	AD	d12	20	1	20
r2	AD	d13	20	1	20
r2	AD	d14	20	1	20
r2	AD	d15	20	1	20
r2	TBMD	d1	20	1	20
r2	TBMD	d2	20	1	20
r2	TBMD	d3	20	1	20
r2	TBMD	d4	20	1	20
r2	TBMD	d5	20	1	20
r2	TBMD	d6	20	1	20
r2	TBMD	d7	20	1	20
r2	TBMD	d12	20	1	20
r2	TBMD	d13	20	1	20
r2	TBMD	d14	20	1	20
r2	TBMD	d15	20	1	20

ASW in region r12 is scheduled for all fifteen days of the planning horizon. On two particular days, nine and ten, ASW is accomplished to the 0.5 level. FFG 52 performs ASW on these days, but is a degraded ASW platform.

SubIntel in region r16 is gapped after the seventh day. There is a two-day gap until another submarine completes the transit and takes over the mission on day ten.

4. Fourth Run—Allow Unlimited Stall Days

The fourth run yields the highest objective value of 3503.50, with an upper bound of 3507.50. This final run of our scenario shows full completion of each of the three highest priority missions. From an enumeration standpoint, the schedules are less diverse. As ships are allowed to delay longer in one region, more schedules have the same regions repeating. It is important to enumerate enough varied schedules to have confidence in finding the optimal set of employment schedules, as opposed to finding the best one of a limited set. Table 8 captures a selected portion of the mission completions for the missions of interest, and Table 9 shows the employment schedules for the ships involved in the region r2 TBMD mission and the region r16 SubIntel mission.

Table 8. Mission Accomplishments for Selected High Priority Missions. In the fourth scenario run, all three high priority missions are fully accomplished on each day of the planning horizon. This table presents selected results. For region r2 missions, a scan of Appendix F shows that CG 61 and DDG 54 begin the scenario in region r2 performing AD and TBMD. CG 61 remains through day thirteen, and DDG 54 remains through day fourteen. On day five, DDG 53 moves into the region and stays through day fourteen. CG 72 and DDG 90 move into the region to close out the scenario on day fifteen.

MISSION ACCOMPLISHMENT					
Region	**Mission**	**Day**	**Value**	**Effort**	**Achieved**
r2	TBMD	d1	20	1	20
r2	TBMD	d2	20	1	20
r2	TBMD	d3	20	1	20
r2	TBMD	d4	20	1	20
		...			
r2	TBMD	d12	20	1	20
r2	TBMD	d13	20	1	20
r2	TBMD	d14	20	1	20
r2	TBMD	d15	20	1	20
r12	ASW	d1	20	1	20
r12	ASW	d2	20	1	20
r12	ASW	d3	20	1	20
r12	ASW	d4	20	1	20
		...			
r12	ASW	d12	20	1	20
r12	ASW	d13	20	1	20
r12	ASW	d14	20	1	20
r12	ASW	d15	20	1	20
r16	SubIntel	d1	20	1	20
r16	SubIntel	d2	20	1	20
r16	SubIntel	d3	20	1	20
r16	SubIntel	d4	20	1	20
		...			
r16	SubIntel	d12	20	1	20
r16	SubIntel	d13	20	1	20
r16	SubIntel	d14	20	1	20
r16	SubIntel	d15	20	1	20

Table 9. Employment Schedule for SSN 717. SSN 717 is assigned to region r16 on day one of the scenario. With *max stall days* unlimited and the long distance to adjacent regions, this submarine is allowed to remain in region r16 and complete the high-priority SubIntel mission.

COMBAT SHIP EMPLOYMENT SCHEDULE				
SSN717	p708340			
d1	r16	SubIntel		
d2	r16	SubIntel		
d3	r16	SubIntel		
d4	r16	SubIntel		
d5	r16	SubIntel		
d6	r16	SubIntel		
d7	r16	SubIntel		
d8	r16	SubIntel		
d9	r16	SubIntel		
d10	r16	SubIntel		
d11	r16	SubIntel		
d12	r16	SubIntel		
d13	r16	SubIntel		
d14	r16	SubIntel		
d15	r16	SubIntel		

C. LESSONS LEARNED

We have found that initial positioning of ships on their first day in theater can have a significant effect on the total mission value obtained by NMP. The operational planner knows the commander's highest priority missions and regions. The planner is also aware of what ships are under his or her commander's operational control and for what time period. We have found that when a high priority mission has a prerequisite mission, e.g., AD is a prerequisite for TBMD, the planner should schedule the prerequisite mission and value it accordingly.

We have noted that increasing stall days can keep ships in place to accomplish important missions in a region. With limited resources or large distances between regions, the max stall days constraint may force ships to leave priority regions. As a result, high-priority missions may be left uncovered while ships are in transit. Planners can solve this issue by increasing the max stall days.

As the constraint max stall days increases, there are more schedules with the same regions repeated. In response, the planner should increase the constraint max schedules

and max schedules per ship to allow NMP to enumerate more varied schedules. More varied schedules increases the likelihood of finding the true optimal schedule. The number is “high enough” when increasing it fails to improve the value of the objective equation.

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V. SUMMARY AND FUTURE IMPROVEMENTS

A. SUMMARY

Maritime component commanders employ forces in support of the combatant commander. When requirements exceed resources, planners must assign available resources efficiently to maximize mission completions. NMP seeks to reduce the time involved in mission planning by taking the planner's inputs and returning a set of optimized ship employment schedules.

NMP uses Microsoft Excel and Visual Basic code to enumerate a set of feasible candidate schedules for each ship subject to the user-defined maximum number of schedules as well as the maximum number of schedules per ship. Excel sends the set of inputs to GAMS which uses a commercial solver to find the optimal set of mission schedules that maximizes the value of assigned missions.

B. FUTURE IMPROVEMENTS

1. Common Operating Picture

Dugan (2007) recommends that NMP interact with the Common Operating Picture. This functionality is not yet realized; however, it should remain a goal that NMP receive automatic updates to ship position and readiness levels, so as to provide daily updates as an operational plan unfolds in real time.

2. Logistics

Replenishment of stores is not addressed in NMP. Every few days a ship must take on fuel, food, weapons, parts, and sometimes transfer personnel. In the current scenario, ships remain available for tasking or transit for the entire planning horizon. Future versions of NMP should explicitly model logistics requirements, possibly through the inclusion of Combat Logistics Force ships, and track re-supply schedules and weapons load outs.

The majority of the ships in this scenario have degradations. The addition of logistics to this model would add to the realism of the solution and allow degraded units to become full mission capable over the course of the scenario.

3. User Interface

Further refinement of the NMP user interface is possible. The raw output is a lengthy text file and a few Excel worksheets. Refinement of the output reports which highlight the gaps in mission coverage would be helpful to the operational planner. Automatic output of Gantt charts showing ship employment schedules would save the user much preparation time for briefing the commander.

4. Improve Enumeration for More Diverse Schedules

As the planning horizon and number of regions grow, the total number of possible schedules grows exponentially. The current version of NMP breaks down at about one million total schedules due to system memory requirements. Instead of increasing the total number of schedules used in the optimization model, it would be more productive to produce a more diverse subset of feasible schedules. This would be accomplished by a modification of the enumeration algorithm itself, or by using another model or algorithm to filter millions of schedules down to a few thousand (per ship) that are likely to be useful.

5. Platform Pre-positioning

Initial positioning of ships for the first scenario day has a major impact on the solutions achieved by NMP. The next version of NMP can be expanded to allow flexibility in the first day's schedules. A minor modification to the interface, which does not change the underlying model, would incorporate a new column, "Pre-positioned," into the Ships worksheet. If this column is checked for a particular ship, then all schedules for that ship would begin in the region specified by the user. Otherwise, a greedy start-point generator would position the ships in regions with high-valued missions. This modification would allow the operational commander more flexibility for the initial day of the planning horizon.

APPENDIX A. REGION AND ARC DEFINITIONS

The following table displays the NMP region set for the scenario presented in Chapter IV. We present 16 regions and 25 arcs. For example, region r16 is defined at 40 degrees north latitude and 130 degrees east longitude. Region r16 is connected to r13 at a distance of 150 nautical miles and to r15 at a distance of 165.7 nautical miles.

Region	LON	LAT		Arcs		Length(nm)
r1	123	35		r1	r2	77.4
r2	124	36		r1	r3	57.7
r3	124	34.5		r2	r3	90
r4	125	35		r2	r4	77.4
r5	125	33.56		r2	r7	74.3
r6	125.25	32		r3	r4	57.7
r7	125.5	36.25		r3	r5	75.2
r8	126.6	32.5		r4	r7	78.9
r9	128	32.5		r4	r5	86.4
r10	129	33.8		r5	r6	94.5
r11	130	36		r5	r8	102.6
r12	130.2	34.5		r6	r8	74.8
r13	130	37.5		r8	r9	70.9
r14	131.5	36		r9	r10	92.8
r15	131.5	37.5		r10	r12	72.9
r16	130	40		r11	r12	90.6
				r11	r13	90
				r11	r14	72.8
				r11	r15	115.4
				r12	r14	110.3
				r13	r14	115.4
				r13	r15	71.4
				r14	r15	90
				r13	r16	150
				r15	r16	165.7

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APPENDIX B. FULL SHIP SET

The following table displays the full NMP ship worksheet for the scenario presented in Chapter IV. Inputs include hull number, ship name, availability flag, ship class, ship type, start day, start region, and the available CMC set for that ship. For example, USS Curtis Wilbur, DDG 54, is available in the scenario. It is a guided missile destroyer, DDG, classified as a combat ship. Curtis Wilbur begins on day one in region r4 and has CMC set C11, C15, and C17 (see Appendix C for the full listing of CMC sets in our scenario). Note that all ship types are listed as combat ships. This column enables future development to include logistics forces.

Ship	Name	Avail	Class	Type	Start Day	Start Region	CMCs		
CG61	Monterey	x	CG	COMBAT	1	r2	C1	C5	C7
CG66	Hue City	x	CG	COMBAT	1	r13	C2	C5	C8
CG72	Vella Gulf	x	CG	COMBAT	4	r7	C3	C6	C9
CG58	Philippine Sea	x	CG	COMBAT	7	r10	C4	C5	C10
CG63	Cowpens		CG	COMBAT	50	r20	C1		
CG56	San Jacinto		CG	COMBAT	50	r20	C1		
CG65	Chosin		CG	COMBAT	50	r20	C1		
DDG53	John Paul Jones	x	DDG	COMBAT	1	r1	C11	C15	C17
DDG54	Curtis Wilbur	x	DDG	COMBAT	1	r4	C11	C15	C17
DDG86	Shoup	x	DDG	COMBAT	1	r9	C12	C15	C18
DDG90	Chaffee	x	DDG	COMBAT	1	r7	C12	C15	C18
DDG100	Kidd	x	DDG	COMBAT	4	r5	C13	C16	C19
DDG80	Roosevelt	x	DDG	COMBAT	4	r13	C11	C15	C17
DDG104	Sterett	x	DDG	COMBAT	4	r4	C11	C15	C17
DDG97	Halsey	x	DDG	COMBAT	7	r11	C11	C15	C17
DDG78	Porter		DDG	COMBAT	50	r20	C11		
DDG74	McFaul		DDG	COMBAT	50	r20	C11		
DDG72	Mahan		DDG	COMBAT	50	r20	C11		
DDG75	Donald Cook		DDG	COMBAT	50	r20	C11		
DDG71	Ross		DDG	COMBAT	50	r20	C11		
DDG62	Fitzgerald		DDG	COMBAT	50	r20	C11		
DDG67	Cole		DDG	COMBAT	50	r20	C11		

Ship	Name	Avail	Class	Type	Start Day	Start Region	CMCs		
FFG48	Vandegrift	x	FFG	COMBAT	4	r10	C21	C25	
FFG52	Carr	x	FFG	COMBAT	4	r11	C22	C25	
FFG47	Nicholas	x	FFG	COMBAT	7	r8	C23	C26	
FFG60	Rodney M Davis		FFG	COMBAT	50	r20	C21		
LCS1	Freedom		LCS	COMBAT	50	r20	C27		
LCS2	Independence		LCS	COMBAT	50	r20	C27		
SSN752	Pasadena	x	SSN	COMBAT	1	r12	C31	C37	
SSN718	Honolulu	x	SSN	COMBAT	6	r7	C34	C37	
SSN717	Olympia	x	SSN	COMBAT	1	r16	C33	C37	
SSN770	Tucson		SSN	COMBAT	50	r20	C31		
SSN706	Albuquerque		SSN	COMBAT	50	r20	C31		
SSN764	Boise		SSN	COMBAT	50	r20	C31		
SSGN726	Ohio		SSGN	COMBAT	50	r20	C38		
MCM6	Devastator		MCM	COMBAT	50	r20	C41		
MCM8	Scout		MCM	COMBAT	50	r20	C41		
MCM10	Warrior		MCM	COMBAT	50	r20	C41		
MCM14	Chief		MCM	COMBAT	50	r20	C41		

APPENDIX C. FULL CMC MATRIX

The following table displays the NMP concurrent mission capability matrix for the scenario presented in Chapter IV. Rows with values less than one represent mission capability degradations. LCS, SSGN, and MCM class ships are available but not used in the scenario. We define available CMCs to enable easy expansion of the scenario. For example, CMC C12 belongs to the DDG class and represents full concurrent mission capability in air defense, surface warfare, strike, and intelligence collection, but degradations to half-capability in antisubmarine warfare and three-quarter capability in naval surface fire support.

		Mission										
Ship Class	CMC	AD	TBMD	ASW	SUW	Strike	NSFS	MIO	MCM	Mine	Intel	SubIntel
CG	C1	1	0	1	1	1	1	0	0	0	1	0
	C2	1	0	0.5	1	1	0.75	0	0	0	1	0
	C3	1	0	1	0.5	1	0.5	0	0	0	1	0
	C4	1	0	0	1	1	1	0	0	0	1	0
	C5	1	0	0	1	1	0	1	0	0	1	0
	C6	1	0	0	0.5	1	0	1	0	0	1	0
	C7	0	1	1	1	1	1	0	0	0	1	0
	C8	0	1	0.5	1	1	0.75	0	0	0	1	0
	C9	0	1	1	0.5	1	0.5	0	0	0	1	0
	C10	0	1	0	1	1	1	0	0	0	1	0
DDG	C11	1	0	1	1	1	1	0	0	0	1	0
	C12	1	0	0.5	1	1	0.75	0	0	0	1	0
	C13	1	0	1	0.5	1	0.5	0	0	0	1	0
	C14	1	0	0	1	1	1	0	0	0	1	0
	C15	1	0	0	1	1	0	1	0	0	1	0
	C16	1	0	0	0.5	1	0	1	0	0	1	0
	C17	0	1	1	1	1	1	0	0	0	1	0
	C18	0	1	0.5	1	1	0.75	0	0	0	1	0
	C19	0	1	1	0.5	1	0.5	0	0	0	1	0
	C20	0	1	0	1	1	1	0	0	0	1	0
FFG	C21	0	0	1	1	0	0	0	0	0	0	0
	C22	0	0	0.5	1	0	0	0	0	0	0	0
	C23	0	0	1	0.5	0	0	0	0	0	0	0
	C24	0	0	0.67	0.67	0	0	0	0	0	0	0
	C25	0	0	0	1	0	0	1	0	0	0	0
	C26	0	0	0	0.5	0	0	1	0	0	0	0

		Mission										
Ship Class	CMC	AD	TBMD	ASW	SUW	Strike	NSFS	MIO	MCM	Mine	Intel	SubIntel
LCS	C27	0	0	1	0	0	0	0	0	0	0	0
	C28	0	0	0	1	0	0	1	0	0	0	0
	C29	0	0	0	0.5	0	0	1	0	0	0	0
	C30	0	0	0	0	0	0	0	1	0	0	0
SSN	C31	0	0	1	1	0	0	0	0	0	0	0
	C32	0	0	1	0.5	0	0	0	0	0	0	0
	C33	0	0	0.5	1	0	0	0	0	0	0	0
	C34	0	0	1	0	0	0	0	0	0	0	0
	C35	0	0	0	0	1	0	0	0	0	0	0
	C36	0	0	0	0	0	0	0	0	1	0	0.5
	C37	0	0	0	0	0	0	0	0	1	0	1
SSGN	C38	0	0	0	0	1	0	0	0	0	0	0
	C39	0	0	0	0	0	0	0	0	1	0	0.5
	C40	0	0	0	0	0	0	0	0	0.5	0	1
MCM	C41	0	0	0	0	0	0	0	1	0	0	0

APPENDIX D. FULL MISSION SET

The following table displays the full mission set defined in our scenario. We assign a mission identifier and an include flag. As defined in Chapter III, a mission is a mission type required in a region for a given time period with a defined value and prerequisite missions. For example, mission m15, included in the scenario, is a NSFS mission required in region r4 on days five through eight. Mission m15 has a value of 5 and requires AD as a prerequisite. Note that m80 is inserted in region r2 for the second and succeeding scenario runs.

Mission	Include	Type	Region	Start Day	End Day	Value	Requires	
m1	x	MIO	r1	1	4	9	AD	
m2	x	AD	r1	1	4	7		
m3	x	ASW	r1	1	4	8	AD	SUW
m4	x	Intel	r1	1	4	7		
m5	x	TBMD	r2	1	15	20	AD	
m80	x	AD	r2	1	15	20		
m6	x	MIO	r3	1	4	5	AD	
m7	x	AD	r3	1	15	3		
m8	x	ASW	r3	1	4	4	AD	
m9	x	Intel	r3	1	15	3		
m10	x	MIO	r4	1	4	7	AD	
m11	x	AD	r4	1	15	5		
m12	x	ASW	r4	1	4	6	SUW	
m13	x	Intel	r4	1	15	5		
m14	x	Strike	r4	5	11	7	AD	
m15	x	NSFS	r4	5	8	5	AD	
m16	x	SUW	r4	5	11	5	AD	
m17	x	MIO	r4	12	15	3	AD	
m18	x	ASW	r4	12	15	3	SUW	
m19	x	MIO	r5	1	4	5	AD	
m20	x	AD	r5	1	15	3		
m21	x	ASW	r5	1	4	4	SUW	
m22	x	Intel	r5	1	15	3		
m23	x	Strike	r5	5	11	15	AD	
m24	x	NSFS	r5	5	8	7	AD	
m25	x	SUW	r5	5	11	7	AD	
m26	x	MIO	r5	12	15	5	AD	
m27	x	ASW	r5	12	15	5	SUW	
m28	x	MIO	r7	1	4	9	AD	
m29	x	AD	r7	1	15	7		
m30	x	ASW	r7	1	15	8	AD	SUW

Mission	Include	Type	Region	Start Day	End Day	Value	Requires	
m31	x	Intel	r7	1	15	7		
m32	x	Strike	r7	5	11	15	AD	
m33	x	NSFS	r7	5	8	7	AD	
m34	x	SUW	r7	5	11	7	AD	
m35	x	MIO	r7	12	15	5	AD	
m36	x	ASW	r7	12	15	5	SUW	
m37	x	MIO	r8	1	4	5	AD	
m38	x	AD	r8	1	15	3		
m39	x	ASW	r8	1	4	4	SUW	
m40	x	Intel	r8	1	15	3		
m41	x	Strike	r8	5	11	5	AD	
m42	x	NSFS	r8	5	8	3	AD	
m43	x	SUW	r8	5	11	3	AD	
m44	x	MIO	r9	1	4	7	AD	
m45	x	AD	r9	1	15	5		
m46	x	ASW	r9	1	4	6	SUW	
m47	x	Intel	r9	1	15	5		
m48	x	Strike	r9	5	11	5	AD	
m49	x	NSFS	r9	5	8	3	AD	
m50	x	SUW	r9	5	11	3	AD	
m51	x	MIO	r10	1	4	5	AD	
m52	x	AD	r10	1	15	3		
m53	x	ASW	r10	1	4	4	SUW	
m54	x	Intel	r10	1	15	3		
m55	x	Strike	r10	5	11	7	AD	
m56	x	NSFS	r10	5	8	5	AD	
m57	x	SUW	r10	5	11	5	AD	
m58	x	MIO	r10	12	15	3	AD	
m59	x	ASW	r10	12	15	3	SUW	
m60	x	MIO	r11	1	4	7	AD	
m61	x	AD	r11	1	15	5		
m62	x	ASW	r11	1	4	6	SUW	
m63	x	Intel	r11	1	15	5		
m64	x	Strike	r11	5	11	7	AD	
m65	x	NSFS	r11	5	8	5	AD	
m66	x	SUW	r11	5	11	5	AD	
m67	x	MIO	r11	12	15	3	AD	
m68	x	ASW	r11	12	15	3	SUW	
m69	x	ASW	r12	1	15	20		
m70	x	MIO	r13	1	4	9	AD	
m71	x	AD	r13	1	15	7		
m72	x	ASW	r13	1	15	8	AD	SUW
m73	x	Intel	r13	1	15	7		
m74	x	Strike	r13	5	11	15	AD	
m75	x	NSFS	r13	5	8	7	AD	
m76	x	SUW	r13	5	11	7	AD	
m77	x	MIO	r13	12	15	5	AD	
m78	x	ASW	r13	12	15	5	SUW	
m79	x	SubIntel	r16	1	15	20		

APPENDIX E. EMPLOYMENT SCHEDULE SET—INITIAL RUN

The following table displays the full NMP-produced set of optimal employment schedules for the first run of our scenario. The first run includes no pre-assigned AD in region r2 and 3 max stall days. For each ship, the schedule number is listed, as well as the employment data for each day of the planning horizon. Day, region, CMC, and mission types are listed. Note that only those mission types which accrue value are listed. In many instances, this results in the display of a subset of the listed CMC. For full description of the CMC, refer to Appendix C.

COMBAT SHIP EMPLOYMENT SCHEDULE								
CG61	p3							
d1	r2	C5	AD					
d2	r2	C7						
d3	r2	C7						
d4	r3	C5	AD	MIO	Intel			
d5	r3	C5	AD	Intel				
d6	r3	C5	AD	Intel				
d7	r4	C1	AD	SUW	Strike	NSFS	Intel	
d8	r4	C1	AD	SUW	Strike	NSFS	Intel	
d9	r4	C5	AD	SUW	Strike	Intel		
d10	r5	C1	AD	SUW	Strike	Intel		
d11	r5	C5	AD	SUW	Strike	Intel		
d12	r5	C5	AD	SUW	MIO	Intel		
d14	r7	C1	AD	ASW	SUW	Intel		
d15	r4	C1	AD	ASW	SUW	Intel		
CG66	p60800							
d1	r13	C5	AD	SUW	MIO	Intel		
d2	r13	C5	AD	SUW	MIO	Intel		
d3	r13	C5	AD	SUW	MIO	Intel		
d4	r15	INACTIVE						
d7	r1	INACTIVE						
d8	r2	C8						
d9	r2	C8						
d10	r2	C8						
d11	r3	C5	AD	Intel				
d12	r3	C2	AD	Intel				
d13	r3	C5	AD	Intel				
d14	r4	C5	AD	SUW	MIO	Intel		
d15	r7	C5	AD	SUW	MIO	Intel		

CG72	p83337							
d4	r7	C6	AD	MIO	Intel			
d5	r7	C3	AD	SUW	Strike	NSFS	Intel	
d6	r7	C3	AD	SUW	Strike	NSFS	Intel	
d8	r8	C3	AD	SUW	Strike	NSFS	Intel	
d9	r8	C6	AD	SUW	Strike	Intel		
d10	r8	C3	AD	SUW	Strike	Intel		
d11	r9	C6	AD	SUW	Strike	Intel		
d12	r9	C3	AD	Intel				
d13	r10	C9	ASW	SUW	Intel			
d14	r10	C9	ASW	SUW	Intel			
d15	r10	C9	ASW	SUW	Intel			
CG58	p125012							
d7	r10	C4	AD	SUW	Strike	NSFS	Intel	
d8	r10	C4	AD	SUW	Strike	NSFS	Intel	
d9	r10	C4	AD	SUW	Strike	Intel		
d11	r11	C4	AD	SUW	Strike	Intel		
d12	r11	C5	AD	MIO	Intel			
d13	r13	C5	AD	SUW	MIO	Intel		
d14	r11	C5	AD	MIO	Intel			
d15	r11	C5	AD	MIO	Intel			
DDG53	p166670							
d1	r1	C15	AD	SUW	MIO	Intel		
d2	r1	C15	AD	SUW	MIO	Intel		
d3	r1	C15	AD	SUW	MIO	Intel		
d4	r2	C17						
d5	r2	C17						
d6	r2	C17						
d7	r3	C11	AD	Intel				
d8	r3	C15	AD	Intel				
d9	r3	C15	AD	Intel				
d10	r4	C11	AD	SUW	Strike	Intel		
d11	r4	C11	AD	SUW	Strike	Intel		
d12	r4	C11	AD	ASW	SUW	Intel		
d13	r5	C15	AD	SUW	MIO	Intel		
d14	r5	C15	AD	MIO	Intel			
d15	r8	C11	AD	Intel				
DDG54	p208336							
d1	r4	C15	AD	SUW	MIO	Intel		
d2	r4	C15	AD	SUW	MIO	Intel		
d3	r4	C15	AD	SUW	MIO	Intel		
d4	r5	C11	AD	ASW	SUW	Intel		
d5	r5	C11	AD	SUW	Strike	NSFS	Intel	
d6	r5	C11	AD	SUW	Strike	NSFS	Intel	
d8	r7	C11	AD	ASW	SUW	Strike	NSFS	Intel
d9	r7	C15	AD	SUW	Strike	Intel		
d11	r8	C11	AD	SUW	Strike	Intel		
d12	r8	C15	AD	Intel				
d13	r9	C11	AD	Intel				
d14	r9	C15	AD	Intel				
d15	r9	C15	AD	Intel				

DDG86	p250039							
d1	r9	C15	AD	SUW	MIO	Intel		
d2	r9	C15	AD	SUW	MIO	Intel		
d3	r9	C15	AD	SUW	MIO	Intel		
d4	r10	C15	AD	SUW	MIO	Intel		
d5	r10	C12	AD	SUW	Strike	NSFS	Intel	
d6	r10	C12	AD	SUW	Strike	NSFS	Intel	
d8	r11	C12	AD	SUW	Strike	NSFS	Intel	
d9	r11	INACTIVE						
d10	r12	C12	ASW					
d12	r15	INACTIVE						
d13	r13	C18	ASW	SUW	Intel			
d14	r13	C15	AD	SUW	MIO	Intel		
d15	r13	C12	AD	ASW	SUW	Intel		
DDG90	p291685							
d1	r7	C15	AD	SUW	MIO	Intel		
d2	r7	C15	AD	SUW	MIO	Intel		
d3	r7	C15	AD	SUW	MIO	Intel		
d5	r8	C12	AD	SUW	Strike	NSFS	Intel	
d6	r8	C12	AD	SUW	Strike	NSFS	Intel	
d7	r9	C12	AD	SUW	Strike	NSFS	Intel	
d8	r9	C12	AD	SUW	Strike	NSFS	Intel	
d9	r9	C15	AD	SUW	Strike	Intel		
d10	r10	C15	AD	SUW	Strike	Intel		
d11	r10	C12	AD	SUW	Strike	Intel		
d12	r12	INACTIVE						
d13	r10	C15	AD	SUW	MIO	Intel		
d14	r10	C15	AD	SUW	MIO	Intel		
d15	r10	C15	AD	SUW	MIO	Intel		
DDG100	p373892							
d4	r5	C16	AD	SUW	MIO	Intel		
d5	r5	C13	AD	SUW	Strike	NSFS	Intel	
d6	r5	C13	AD	SUW	Strike	NSFS	Intel	
d8	r7	C13	AD	ASW	SUW	Strike	NSFS	Intel
d9	r7	C13	AD	ASW	SUW	Strike	Intel	
d10	r7	C13	AD	SUW	Strike	Intel		
d12	r8	C16	AD	Intel				
d13	r8	C13	AD	Intel				
d14	r8	C13	AD	Intel				
d15	r5	C16	AD	SUW	MIO	Intel		
DDG80	p390587							
d4	r13	C15	AD	SUW	MIO	Intel		
d5	r13	C11	AD	ASW	SUW	Strike	NSFS	Intel
d6	r13	C11	AD	ASW	SUW	Strike	NSFS	Intel
d7	r15	INACTIVE						
d10	r1	INACTIVE						
d11	r2	C17						
d12	r2	C17						
d13	r2	C11						
d14	r3	C11	AD	Intel				
d15	r2	C15	AD					

DDG104	p416672							
d4	r4	C15	AD	SUW	MIO	Intel		
d5	r4	C11	AD	SUW	Strike	NSFS	Intel	
d6	r4	C11	AD	SUW	Strike	NSFS	Intel	
d7	r5	C11	AD	SUW	Strike	NSFS	Intel	
d8	r5	C11	AD	SUW	Strike	NSFS	Intel	
d9	r5	C11	AD	SUW	Strike	Intel		
d11	r7	C11	AD	ASW	SUW	Strike	Intel	
d12	r7	C11	AD	ASW	SUW	Intel		
d13	r7	C11	AD	ASW	SUW	Intel		
d14	r2	INACTIVE						
d15	r2	C17	TBMD					
DDG97	p458415							
d7	r11	C11	AD	SUW	Strike	NSFS	Intel	
d8	r11	C11	AD	SUW	Strike	NSFS	Intel	
d9	r11	C15	AD	SUW	Strike	Intel		
d10	r13	C11	AD	ASW	SUW	Strike	Intel	
d11	r13	C11	AD	ASW	SUW	Strike	Intel	
d12	r13	C11	AD	ASW	SUW	Intel		
d13	r11	C11	AD	ASW	SUW	Intel		
d14	r13	C11	AD	ASW	SUW	Intel		
d15	r13	C17	ASW	SUW	Intel			
FFG48	p500099							
d4	r10	C21	ASW	SUW				
d5	r10	C25	SUW					
d6	r10	C25	SUW					
d8	r11	INACTIVE						
d9	r11	C21	SUW					
d10	r13	INACTIVE						
d11	r13	INACTIVE						
d12	r15	INACTIVE						
d13	r13	C21	ASW	SUW				
d14	r13	C21	ASW	SUW				
d15	r13	C21	ASW	SUW				
FFG52	p541686							
d4	r11	C22	ASW	SUW				
d5	r11	INACTIVE						
d6	r11	INACTIVE						
d7	r12	C22	ASW					
d8	r12	C22	ASW					
d9	r12	C22	ASW					
d11	r13	C22	ASW	SUW				
d12	r13	C25	SUW	MIO				
d13	r11	C25	SUW	MIO				
d14	r13	C22	ASW	SUW				
d15	r13	C25	SUW	MIO				

FFG47	p583365							
d7	r8	INACTIVE						
d8	r8	C26	SUW					
d9	r8	C26	SUW					
d10	r5	INACTIVE						
d11	r5	INACTIVE						
d12	r5	INACTIVE						
d14	r7	C26	SUW	MIO				
d15	r7	INACTIVE						
SSN752	p646856							
d1	r12	C31	ASW					
d2	r12	C31	ASW					
d3	r12	C31	ASW					
d5	r13	C31	ASW	SUW				
d6	r13	C31	ASW	SUW				
d7	r15	INACTIVE						
d9	r16	C37	SubIntel					
d12	r2	INACTIVE						
d13	r4	C31	ASW	SUW				
d14	r4	C31	ASW	SUW				
d15	r7	C31	ASW	SUW				
SSN718	p666683							
d6	r7	C34						
d8	r8	INACTIVE						
d10	r10	INACTIVE						
d11	r12	C34	ASW					
d13	r15	INACTIVE						
d15	r16	C37	SubIntel					
SSN717	p719267							
d1	r16	C37	SubIntel					
d2	r16	C37	SubIntel					
d3	r16	C37	SubIntel					
d6	r1	INACTIVE						
d7	r3	INACTIVE						
d8	r4	C33	SUW					
d9	r4	C33	SUW					
d10	r4	C33	SUW					
d11	r5	C33	SUW					
d12	r5	C33	ASW	SUW				
d13	r5	C33	ASW	SUW				
d14	r4	INACTIVE						
d15	r5	C33	ASW	SUW				

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APPENDIX F. EMPLOYMENT SCHEDULE SET—FOURTH RUN

The following table displays the full NMP-produced set of optimal employment schedules for the fourth run of our scenario. The table includes the explicitly assigned AD mission in region r2 and 15 max stall days. As in Appendix E, each ship and its schedule number are listed, as well as the employment data for each day of the planning horizon. Day, region, CMC, and mission types are listed. Again note that only those mission types which accrue value are listed. For full description of the CMC, refer to Appendix C.

COMBAT SHIP EMPLOYMENT SCHEDULE								
CG61	p4							
d1	r2	C5	AD					
d2	r2	C7	TBMD					
d3	r2	C1	AD					
d4	r2	C5	AD					
d5	r2	C1	AD					
d6	r2	C7	TBMD					
d7	r2	C7	TBMD					
d8	r2	C1	AD					
d9	r2	C1	AD					
d10	r2	C7	TBMD					
d11	r2	C7	TBMD					
d12	r2	C7	TBMD					
d13	r2	C7	TBMD					
d14	r2	C1	AD					
d15	r7	C5	AD	SUW	MIO	Intel		
CG66	p41685							
d1	r13	C5	AD	SUW	MIO	Intel		
d2	r13	C5	AD	SUW	MIO	Intel		
d3	r13	C5	AD	SUW	MIO	Intel		
d4	r13	C5	AD	SUW	MIO	Intel		
d5	r13	C2	AD	ASW	SUW	Strike	NSFS	Intel
d6	r13	C2	AD	ASW	SUW	Strike	NSFS	Intel
d7	r13	C2	AD	ASW	SUW	Strike	NSFS	Intel
d8	r13	INACTIVE						
d9	r13	C2	AD	ASW	SUW	Strike	Intel	
d10	r13	C2	AD	ASW	SUW	Strike	Intel	
d11	r13	C2	AD	ASW	SUW	Strike	Intel	
d12	r13	C5	AD	SUW	MIO	Intel		
d13	r11	C5	AD	SUW	MIO	Intel		
d14	r11	C5	AD	SUW	MIO	Intel		
d15	r11	C5	AD	SUW	MIO	Intel		

CG72	p83343							
d4	r7	C3	AD	ASW	SUW	Intel		
d5	r7	C3	AD	ASW	SUW	Strike	NSFS	Intel
d6	r7	C3	AD	ASW	SUW	Strike	NSFS	Intel
d7	r7	C3	AD	ASW	SUW	Strike	NSFS	Intel
d8	r7	C3	AD	ASW	SUW	Strike	NSFS	Intel
d9	r7	C3	AD	ASW	SUW	Strike	Intel	
d10	r7	C6	AD	SUW	Strike	Intel		
d11	r7	C6	AD	SUW	Strike	Intel		
d12	r7	C3	AD	ASW	SUW	Intel		
d13	r7	C9	ASW	SUW	Intel			
d14	r4	C6	AD	MIO	Intel			
d15	r5	C6	AD	SUW	MIO	Intel		
CG58	p125002							
d7	r10	C4	AD	SUW	Strike	NSFS	Intel	
d8	r10	C4	AD	SUW	Strike	NSFS	Intel	
d9	r10	C4	AD	SUW	Strike	Intel		
d10	r10	C5	AD	SUW	Strike	Intel		
d11	r10	C4	AD	SUW	Strike	Intel		
d12	r10	C5	AD	MIO	Intel			
d13	r10	C5	AD	MIO	Intel			
d14	r10	C5	AD	MIO	Intel			
d15	r10	C5	AD	MIO	Intel			
DDG53	p184524							
d1	r1	C15	AD	SUW	MIO	Intel		
d2	r1	C15	AD	SUW	MIO	Intel		
d3	r1	C15	AD	SUW	MIO	Intel		
d4	r1	C15	AD	MIO	Intel			
d5	r2	C17	TBMD					
d6	r2	C17	TBMD					
d7	r2	C17	TBMD					
d8	r2	INACTIVE						
d9	r2	C17	TBMD					
d10	r2	C17	TBMD					
d11	r2	C17	TBMD					
d12	r2	INACTIVE						
d13	r2	C17	TBMD					
d14	r3	C15	AD	Intel				
d15	r2	C17	TBMD					
DDG54	p208338							
d1	r2	C17	TBMD					
d2	r2	C11	AD					
d3	r2	C17	TBMD					
d4	r2	C17	TBMD					
d5	r2	C17	TBMD					
d6	r2	C11	AD					
d7	r2	C11	AD					
d8	r2	C17	TBMD					
d9	r2	C17	TBMD					
d10	r2	C11	AD					
d11	r2	C15	AD					
d12	r2	C15	AD					
d13	r2	C11	AD					
d14	r2	C17	TBMD					
d15	r4	C11	AD	ASW	SUW	Intel		

DDG86	p250003							
d1	r9	C15	AD	SUW	MIO	Intel		
d2	r9	C15	AD	SUW	MIO	Intel		
d3	r9	C15	AD	SUW	MIO	Intel		
d4	r9	C15	AD	MIO	Intel			
d5	r9	C12	AD	SUW	Strike	NSFS	Intel	
d6	r9	C12	AD	SUW	Strike	NSFS	Intel	
d7	r9	C12	AD	SUW	Strike	NSFS	Intel	
d8	r9	C12	AD	SUW	Strike	NSFS	Intel	
d9	r9	C12	AD	SUW	Strike	Intel		
d10	r9	C15	AD	SUW	Strike	Intel		
d11	r9	C12	AD	SUW	Strike	Intel		
d12	r9	C15	AD	Intel				
d13	r9	C15	AD	Intel				
d14	r9	C15	AD	Intel				
d15	r9	C12	AD	Intel				
DDG90	p291671							
d1	r7	C15	AD	SUW	MIO	Intel		
d2	r7	C15	AD	SUW	MIO	Intel		
d3	r7	C15	AD	SUW	MIO	Intel		
d4	r7	C15	AD	SUW	MIO	Intel		
d5	r7	C12	AD	ASW	SUW	Strike	NSFS	Intel
d6	r7	C12	AD	ASW	SUW	Strike	NSFS	Intel
d7	r7	C12	AD	ASW	SUW	Strike	NSFS	Intel
d8	r7	C12	AD	ASW	SUW	Strike	NSFS	Intel
d9	r7	C15	AD	SUW	Strike	Intel		
d10	r7	C15	AD	SUW	Strike	Intel		
d11	r7	C15	AD	SUW	Strike	Intel		
d12	r7	C15	AD	SUW	MIO	Intel		
d13	r7	C15	AD	SUW	MIO	Intel		
d14	r7	C15	AD	SUW	MIO	Intel		
d15	r2	C12	AD					
DDG100	p361136							
d4	r5	C16	AD	MIO	Intel			
d5	r5	C13	AD	SUW	Strike	NSFS	Intel	
d6	r5	C13	AD	SUW	Strike	NSFS	Intel	
d7	r5	C13	AD	SUW	Strike	NSFS	Intel	
d8	r5	C13	AD	SUW	Strike	NSFS	Intel	
d9	r5	C13	AD	SUW	Strike	Intel		
d10	r5	C16	AD	SUW	Strike	Intel		
d11	r5	C16	AD	SUW	Strike	Intel		
d12	r5	C16	AD	SUW	MIO	Intel		
d13	r5	C13	AD	ASW	SUW	Intel		
d14	r8	C16	AD	Intel				
d15	r8	C13	AD	Intel				
DDG80	p375023							
d4	r13	C11	AD	ASW	SUW	Intel		
d5	r13	C11	AD	ASW	SUW	Strike	NSFS	Intel
d6	r13	C11	AD	ASW	SUW	Strike	NSFS	Intel
d7	r13	C11	AD	ASW	SUW	Strike	NSFS	Intel
d8	r13	C11	AD	ASW	SUW	Strike	NSFS	Intel
d9	r13	C11	AD	ASW	SUW	Strike	Intel	
d10	r13	C11	AD	ASW	SUW	Strike	Intel	
d11	r13	INACTIVE						
d12	r13	C17	ASW	SUW	Intel			
d13	r11	C17	ASW	SUW	Intel			
d14	r11	C11	AD	ASW	SUW	Intel		
d15	r13	C11	AD	ASW	SUW	Intel		

DDG104	p416677							
d4	r4	C15	AD	SUW	MIO	Intel		
d5	r4	C11	AD	SUW	Strike	NSFS	Intel	
d6	r4	C11	AD	SUW	Strike	NSFS	Intel	
d7	r4	C11	AD	SUW	Strike	NSFS	Intel	
d8	r4	C11	AD	SUW	Strike	NSFS	Intel	
d9	r4	C11	AD	SUW	Strike	Intel		
d10	r4	C15	AD	SUW	Strike	Intel		
d11	r4	C15	AD	SUW	Strike	Intel		
d12	r4	C11	AD	ASW	SUW	Intel		
d13	r4	C11	AD	ASW	SUW	Intel		
d14	r5	C11	AD	ASW	SUW	Intel		
d15	r3	C15	AD	Intel				
DDG97	p458354							
d7	r11	C11	AD	SUW	Strike	NSFS	Intel	
d8	r11	C11	AD	SUW	Strike	NSFS	Intel	
d9	r11	C15	AD	SUW	Strike	Intel		
d10	r11	C15	AD	SUW	Strike	Intel		
d11	r11	C11	AD	SUW	Strike	Intel		
d12	r11	C11	AD	ASW	SUW	Intel		
d13	r13	C11	AD	ASW	SUW	Intel		
d14	r13	C11	AD	ASW	SUW	Intel		
d15	r13	C11	AD	ASW	SUW	Intel		
FFG48	p500120							
d4	r10	C21	ASW	SUW				
d5	r10	INACTIVE						
d6	r10	INACTIVE						
d7	r10	C21	SUW					
d8	r10	C21	SUW					
d9	r12	C21	ASW					
d10	r12	C21	ASW					
d11	r12	C21	ASW					
d12	r12	C21	ASW					
d13	r12	C21	ASW					
d14	r12	C21	ASW					
d15	r12	C21	ASW					
FFG52	p541688							
d4	r11	C22	ASW	SUW				
d5	r11	INACTIVE						
d6	r11	INACTIVE						
d7	r11	C25	SUW					
d8	r11	C22	SUW					
d9	r11	INACTIVE						
d10	r11	C25	SUW					
d11	r11	INACTIVE						
d12	r11	C25	SUW	MIO				
d13	r13	C25	SUW	MIO				
d14	r13	C25	SUW	MIO				
d15	r13	C25	SUW	MIO				

FFG47	p599405							
d7	r8	INACTIVE						
d8	r8	INACTIVE						
d9	r8	INACTIVE						
d10	r8	INACTIVE						
d11	r8	INACTIVE						
d12	r5	C23	ASW	SUW				
d13	r5	C26	SUW	MIO				
d14	r5	C26	SUW	MIO				
d15	r5	C23	ASW	SUW				
SSN752	p625242							
d1	r12	C31	ASW					
d2	r12	C31	ASW					
d3	r12	C31	ASW					
d4	r12	C31	ASW					
d5	r12	C31	ASW					
d6	r12	C31	ASW					
d7	r12	C31	ASW					
d8	r12	C31	ASW					
d10	r15	INACTIVE						
d11	r11	INACTIVE						
d12	r13	C31	ASW	SUW				
d13	r13	C31	ASW	SUW				
d14	r13	C31	ASW	SUW				
d15	r11	C31	ASW	SUW				
SSN718	p666673							
d6	r7	C34	ASW					
d7	r7	C34	ASW					
d8	r7	C34	ASW					
d9	r7	C34	ASW					
d10	r7	C34	ASW					
d11	r7	C34	ASW					
d12	r7	C34	ASW					
d13	r7	C34	ASW					
d14	r7	C34	ASW					
d15	r7	C34	ASW					
SSN717	p708340							
d1	r16	C37	SubIntel					
d2	r16	C37	SubIntel					
d3	r16	C37	SubIntel					
d4	r16	C37	SubIntel					
d5	r16	C37	SubIntel					
d6	r16	C37	SubIntel					
d7	r16	C37	SubIntel					
d8	r16	C37	SubIntel					
d9	r16	C37	SubIntel					
d10	r16	C37	SubIntel					
d11	r16	C37	SubIntel					
d12	r16	C37	SubIntel					
d13	r16	C37	SubIntel					
d14	r16	C37	SubIntel					
d15	r16	C37	SubIntel					

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